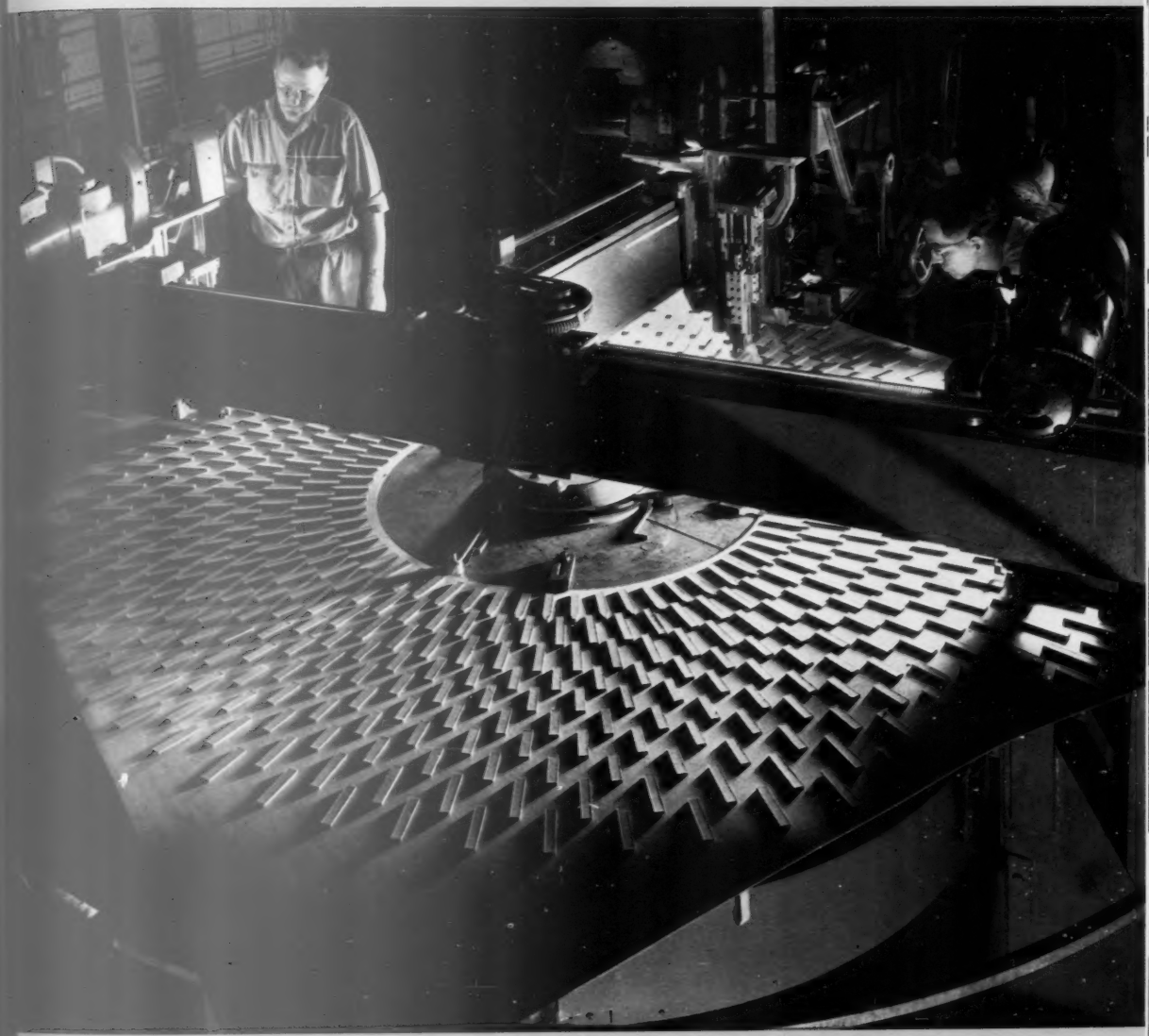
ALLIS-CHALMERS Electrical REVIEW

3RD QUARTER 1952



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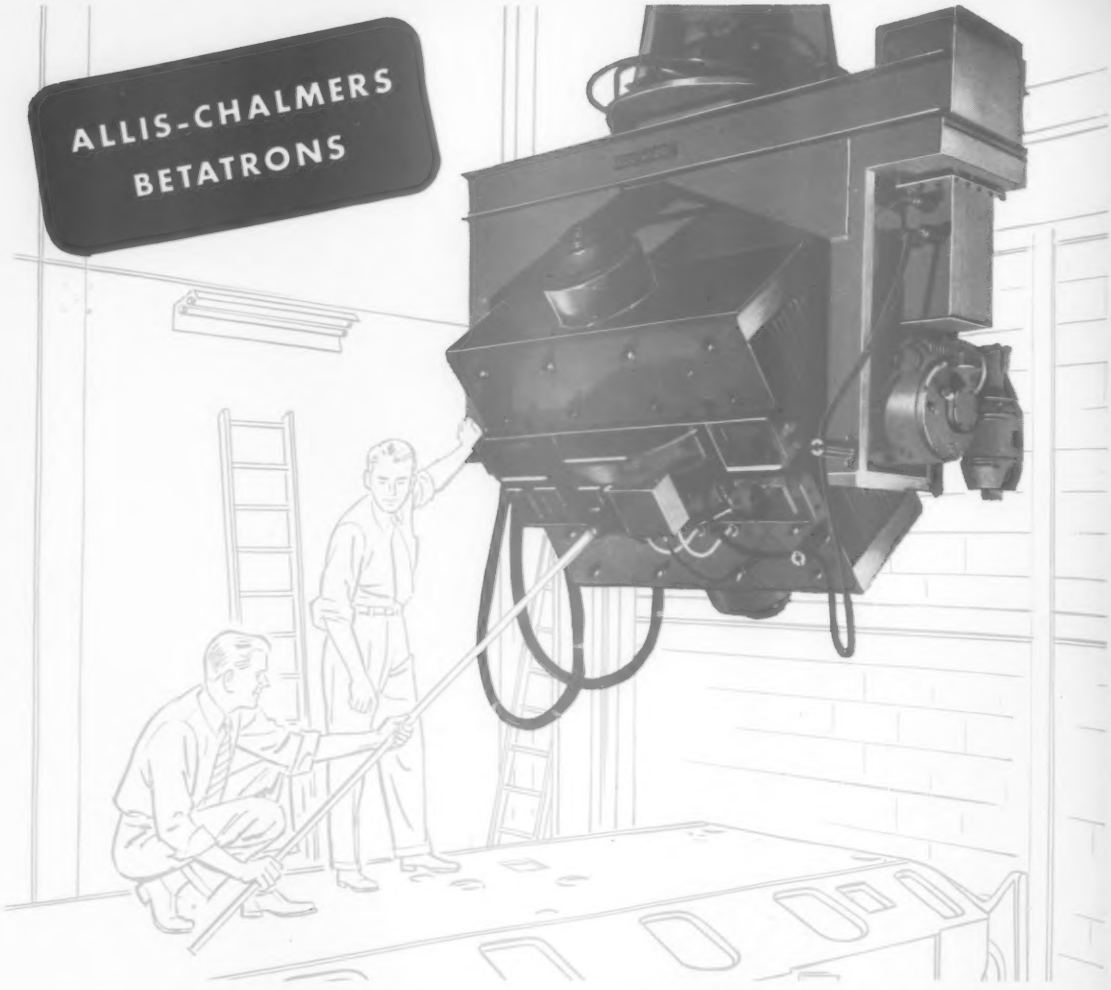

22-MILLION-VOLT "SEEING EYE"

Inspects Heavy Ordnance Parts for Continental Foundry & Machine Company

MOUNTED on a traveling bridge crane is this massive Allis-Chalmers betatron, recently installed by the Continental Foundry and Machine Co., of E. Chicago, Ind., to inspect heavy castings, forgings and weldings. It controls quality of workmanship, saves materials and many hours of labor.

The penetrating "eye" of this betatron can look through sections of solid steel two feet or more thick to detect minute flaws in heavy castings, forgings and weldings. Moreover, the small focal spot inherent in the betatron provides a sharply defined image.

Application of the betatron extends beyond its use in inspection of castings and forgings. It is also used in medical therapy; the inspection of transmissions and motors for internal alignment of parts; and checking for the presence of all internal parts of certain military equipment, before shipment.

For an informative article on the theory and application of the betatron, contact your nearest Picker X-Ray Corporation representative. Ask your Allis-Chalmers District Office for reprint 01R7403 or write Allis-Chalmers, Milwaukee 1, Wisconsin. A-3884

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THE COVER

MATHEMATICAL PRECISION of newly developed equipment saves hours of tedious labor in big transformer manufacture. Within a few minutes a huge fuller board "washer" is placed in position, indexed, and hundreds of oil duct spacer "sticks" are individually glued and pressed into an exact pattern. Proper placement of tens of thousands of these sticks determines cooling efficiency of the transformer.

A-C Staff Photo by M. Durante

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Vol. XVII No. 3

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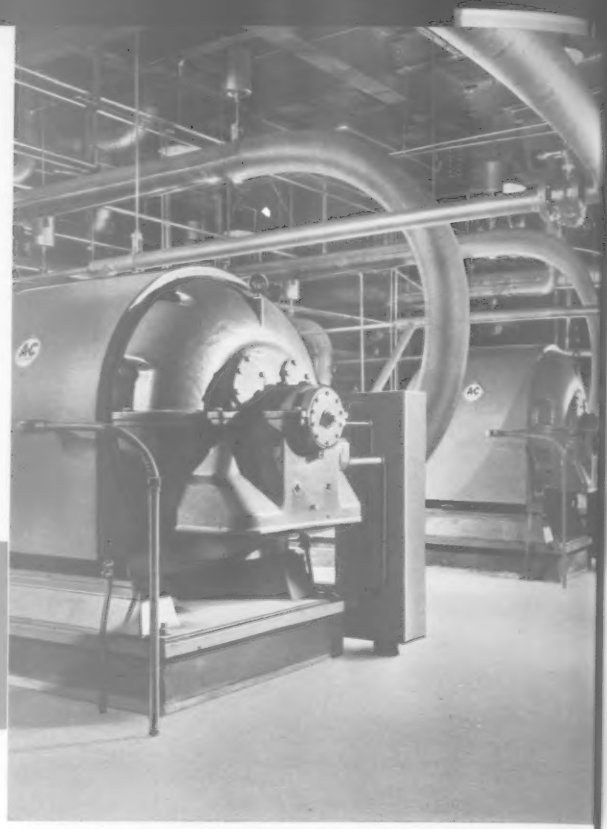
Increasing Building Costs Service Demands and Auxiliary Size Determines the Design of . . .

TODAY'S POWER PLANT MOTORS

by **C. D. LAWTON**
Motor-Generator Section
Allis-Chalmers Mfg. Co.



TYPICAL OF BOILER FEED PUMP MOTORS installed indoors are these 1500-hp, 2300-volt, 3580-rpm squirrel-cage motors.

IN RECENT YEARS, steam turbine generator units have grown in size until now the power required just to drive station auxiliaries is greater than the total output of what was considered a good sized turbo-alternator only a few years ago. For example, boiler feed pump motors of 3500 hp are now operating. Induced draft fans as large as 4000 hp are being considered, and other auxiliaries are growing proportionately.

This growth in equipment size presented several problems, such as: Are indoor or outdoor locations to be chosen? What mechanical construction of rotor and stator is best suited to large size motors that must be reliable? How about bearings and insulation? What is to be done about noise of large, high speed motors? Are enclosures that offer additional protection worth their cost? The answers to these and other questions have had pronounced effect upon the design of auxiliary drive motors, and these new motor developments have been an important factor in making the modern power station possible.

The large essential auxiliary drives are typical examples of how refinements and new developments in motor construction are meeting the rigid operating requirements of modern power plants. These drives represent a large investment, and plant reliability is dependent on them to a large degree.

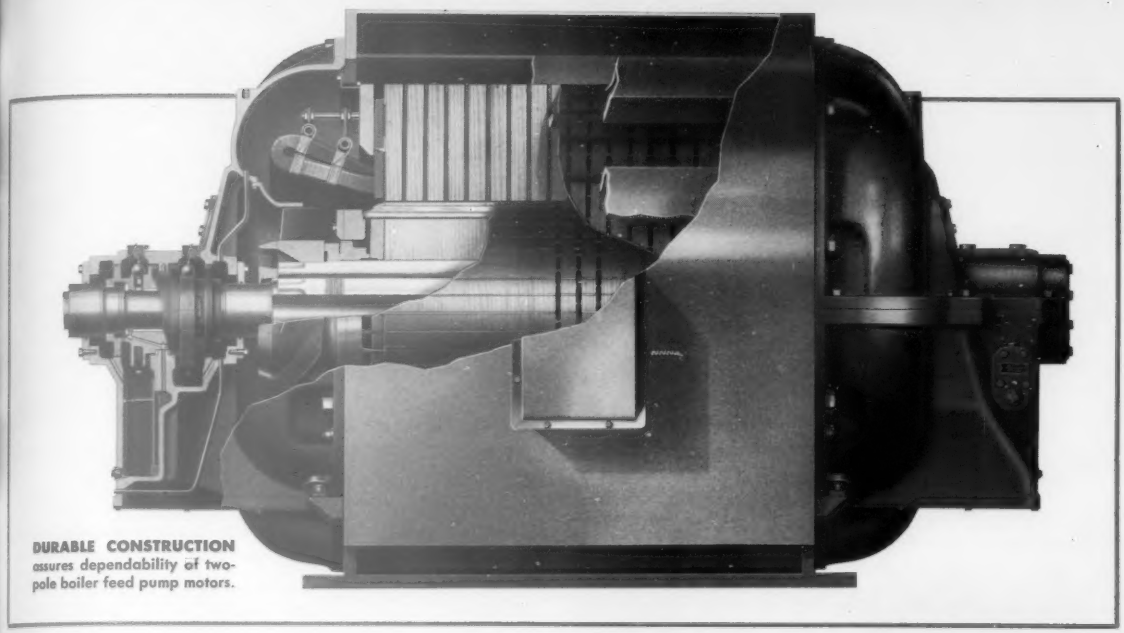
Details influenced by need for reliability

The boiler feed pump is usually the largest auxiliary drive. Being one of the most important in any power plant, its reliability is of prime consideraton.

Boiler feed pump motors are usually operated at approximately 3600 rpm. They are designed for normal starting torque and are started across the line. When located indoors they are usually built open, drip-proof and for 40 C rise service. Service requirements demand that special thought in design be given to trouble-free, year-after-year operation.

To assure service continuity of boiler feed pump motors, their rotors must be designed so that the cage structure cannot fail mechanically. Steps taken include the use of forged end rings and rotor rods of special copper to avoid embrittlement. The rods are shaped so that they cannot vibrate or become loose, and are silver-brazed into the end rings at high temperature. This makes the entire cage structure practically indestructible. Balancing is not done in the end ring, but in a special steel ring bolted to the rotor. Thus the end ring is not weakened mechanically.

Bearing failure caused by shaft currents is minimized by a symmetrical magnetic circuit. To accomplish this, circular rotor punchings are always used. Circular stator punchings are also used, except on the largest sizes—above approximately 2000 hp. At least one bearing is insulated to further safeguard against destructive shaft currents.



DURABLE CONSTRUCTION assures dependability of two-pole boiler feed pump motors.

Special attention is given to the bracing of stator winding end turns to prevent coil movement incident to starting. Except on the smaller size motors, coil insulation consists of a combination of both Class A and B materials. The two types of insulation have a scarfed joint so there is blending and no separation in service.

Dependability is further assured by bracket or housing bearing construction when possible. It results in a more completely housed frame, greater rigidity, easier mounting and alignment. Bracket bearings are used over the entire range of boiler feed pump motors today.

Because of the high speeds at which these motors operate, bearings are liberal in size and each is lubricated by two oil rings, supplemented by forced feed oiling for two-pole motors of 900 hp and above. Special oil and vapor chambers with seals are incorporated with an air pressure chamber at the inside end of each bearing. Air pressure is maintained from the ventilating air intake and relieved through a tube to the outside. This pressure chamber forces out any oil vapor which reaches it and effectively prevents oil vapor from getting to the inside of the motor.

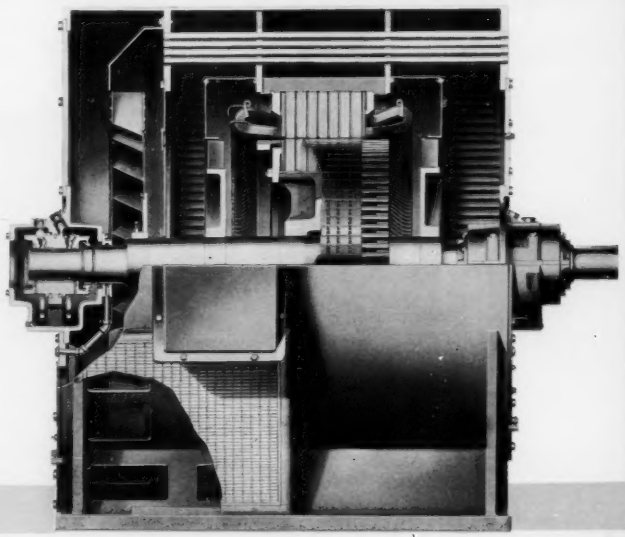
Heat dissipated uniformly

The modern boiler feed pump motor is effectively ventilated for uniform heat dissipation. Long rotors are ventilated and stator coils set deep to allow cool air to flow through the air gap. Because the stator cores are relatively deep, cool air is introduced into the laminations from the back for even cooling of the entire core.

Sound level from 3600-rpm squirrel-cage motors is practically all windage. It is being reduced by rounding edges, eliminating projections, and redesigning air paths and baffling. A good deal of study and research is being given to this problem.

Developments in enclosures for boiler feed pump motors include both water-cooled and totally-enclosed fan-cooled construction. Water-cooling utilizes air-to-water heat exchangers similar to those used for turbo-generators and has several advantages. The water-cooled motor is only slightly larger than normal size, and it is a little more quiet than the usual open drip-proof type. Heat is carried away by the water, and since the motor is completely enclosed, outside dirt cannot enter.

Water-cooling, however, has a number of disadvantages. There is some risk of water leaking into the motor. If the water supply fails, the motor will overheat and shut



OUTSIDE AIR PASSES through tubes to dissipate heat generated within the tube type, totally-enclosed fan-cooled motor.

down. If the safety devices fail to function, the motor may also fail. Water-cooling is not adapted to outdoor operation in northern climates. In addition, there is the need for added equipment and connections for supplying water, and there is always the possibility that water tubes might fill with sediment or other deposits.

A totally-enclosed fan-cooled motor has the major advantages of a water-cooled unit but none of the disadvantages. However, the totally-enclosed fan-cooled motor generally has a slightly higher sound level. Also the ventilating air is discharged into the room. This might be objectionable in certain locations.

Another fairly common motor is the pipe ventilated type. In locations of high ambient temperatures, the motor heat is carried away through ducts, which may be attached to the top or the bottom of the motor. This type of motor is a little more quiet than the open drip-proof motor and is well adapted to warmer climates.

Where variable boiler feed pump output is required, throttling valves have been used in many installations. This is giving way to the hydraulic coupling for variable speed operation. Lately, consideration has also been given to the use of 3600-rpm, wound-rotor induction motors with liquid slip regulators. As yet, their reliability has not been proved to the same extent as squirrel-cage motors. Also, large two-pole, wound-rotor motors have not been built in quantity because they cost about twice as much as similar squirrel-cage motors.

Draft fan motors built for efficiency

Draft fans are also an important major drive in power plants and, again, continuity of service is a prime factor. Due to their location and normal operating speeds which may be anywhere from 514 to 1800 rpm, these motors are somewhat different from the two-pole boiler feed pump types.

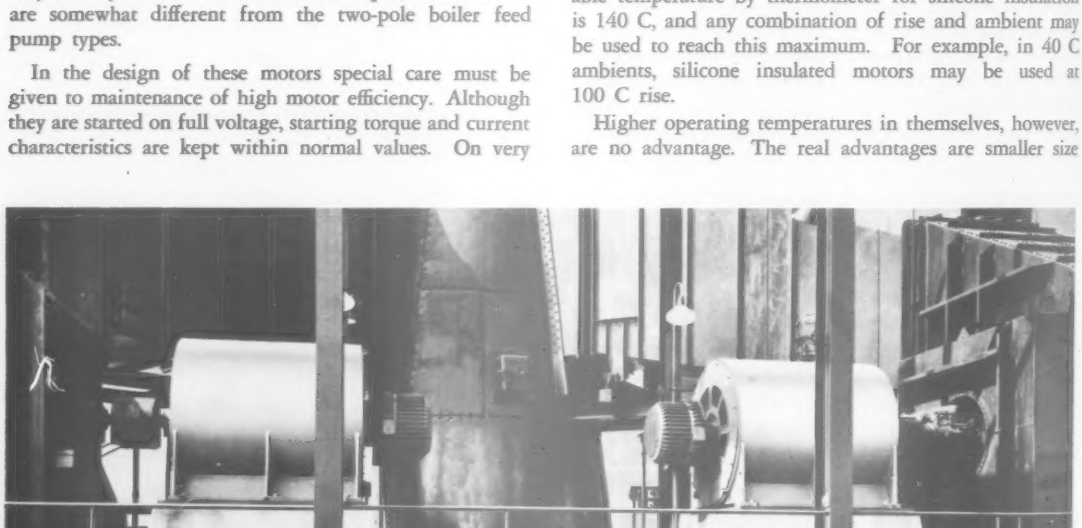
In the design of these motors special care must be given to maintenance of high motor efficiency. Although they are started on full voltage, starting torque and current characteristics are kept within normal values. On very large machines, however, high starting kva may be a problem.

SPEED OF THIS INDUCTION MOTOR driven induced draft fan is varied by a hydraulic coupling. The 1250-hp, 885-rpm, drip-proof squirrel-cage motor has clean lines, accessible features.

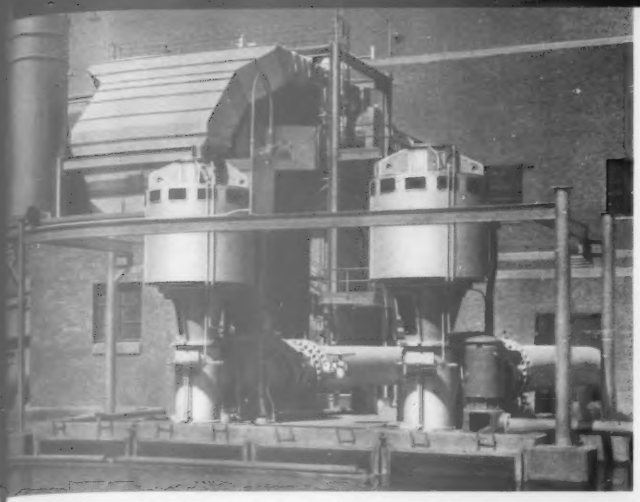
Draft fans, in addition to requiring variable speed operation, are often located in high ambient temperatures and dirty atmospheres. They may be placed outdoors exposed to the weather and to air laden with contaminating particles of fly ash, carbon black, coal dust, salt spray, etc. Ample protection against these conditions must be provided in the design of the motors used on draft fan drives.

Where draft fans are located indoors, their motors are usually drip-proof and 40 C rise. When ambient temperatures are over 50 C, Class B insulation is frequently used, and for extremely high ambient temperatures silicone insulation is sometimes employed. The limiting observable temperature by thermometer for silicone insulation is 140 C, and any combination of rise and ambient may be used to reach this maximum. For example, in 40 C ambients, silicone insulated motors may be used at 100 C rise.

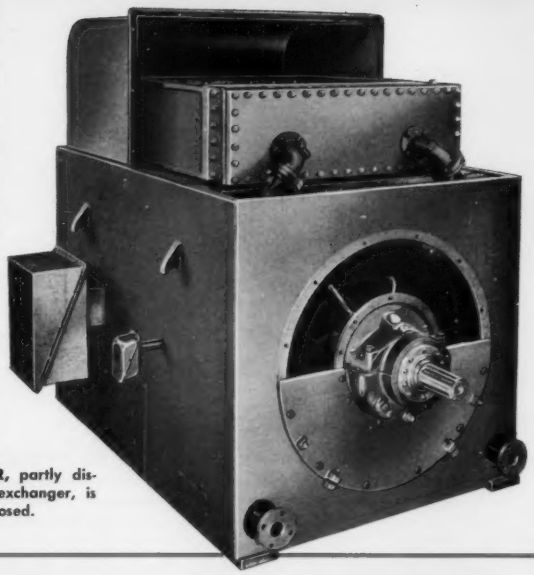
Higher operating temperatures in themselves, however, are no advantage. The real advantages are smaller size



DRIVING INDUCED DRAFT FANS, these totally-enclosed, fan-cooled, 700-hp wound-rotor motors are speed controlled electrically.



OUTDOOR LOCATION of these 400-horsepower, 870-rpm, totally-enclosed fan-cooled motors eliminates costly housing structure.



WATER-COOLED MOTOR, partly disassembled to show heat exchanger, is quiet running, totally enclosed.

and lower weight made possible by these higher operating temperatures. Maximum or pull-out torque, of importance where severe voltage fluctuations occur, is sometimes sacrificed in these smaller motors. Lower temperature rise silicone-insulated motors are frequently used where there is question of overloading at some future date. In this manner an increased draft fan load can be taken care of when boilers are pushed to their maximum capacity.

Variable fan output is being accomplished in a number of ways. Damper control is one of the older methods. Dual drive, using two squirrel-cage motors, one high speed and the other slow speed, is another method long used. Recent years have seen a trend toward hydraulic and electric couplings with squirrel-cage motors. Even more recently, installations of wound-rotor motors with liquid slip regulators have been made. They are giving good performance. This is due to recent developments and improvements in both liquid slip regulators and totally-enclosed, fan-cooled wound-rotor motors. These totally-enclosed fan-cooled motors do not have the ills of the previously used open type, and they approach the reliability and performance of time tried squirrel-cage motors.

Because of the adverse operating conditions surrounding draft fan drives, there is a trend toward totally-enclosed fan-cooled enclosures regardless of location or motor application. Even for indoor service, totally-enclosed fan-cooled motors are often preferred, especially if there is danger of disastrous steam leaks or fly ash accumulation. The modern, totally-enclosed fan-cooled motor is practically self-cleaning, but should cleaning become necessary because of extreme atmospheric conditions it is usually possible to do the job while the motor remains in service.

Totally-enclosed fan-cooled motors are ideal for outdoor service, particularly in locations such as sea coast areas, northern latitudes where heavy snow is encountered, dust storm and hurricane areas.

Motors move outdoors

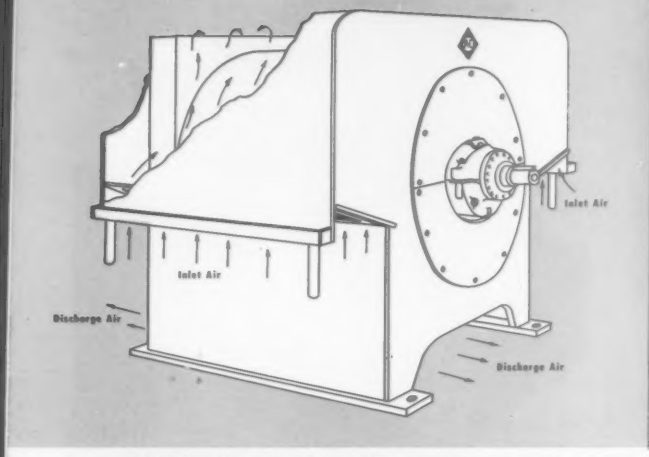
The high cost of present day power plant building construction is resulting in a greater proportion of outdoor auxiliaries. A study of building costs versus equipment protection costs shows outdoor locations are frequently worth while. It must be remembered that, for outdoor locations, better motor protection will result in lower maintenance costs and greater reliability of operation.

In less severe locations, the protection of a totally-enclosed fan-cooled motor is not always necessary. This has led to the recent development of a motor enclosure in which protection is carried far beyond splash-proof construction. It differs from totally-enclosed fan-cooled design in that the ambient air passes completely through the ventilating system of the motor's interior. This new enclosure may be called a weather-protected type.

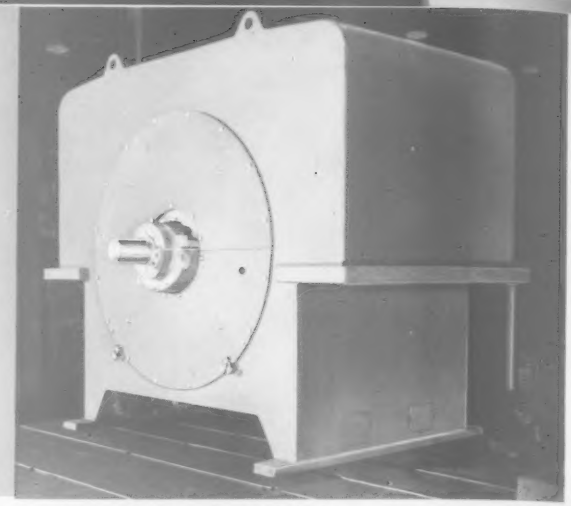
These motors are designed to keep out wind-driven heavy moisture. They have very low intake air velocity. Air intakes are kept at considerable height above ground level to prevent dust and dirt from entering the machine during periods of dry weather. Intakes are screened to prevent larger particles such as papers and leaves from entering the motors. Where necessary intake air filters can be provided.

Heavy rain particles cannot be drawn into the motor because the air intake velocity is low, being kept below 600 feet a minute. For example, in this machine intake air moves vertically upward from intakes at the center line on the sides of the motor into a greatly expanded air space, thereby lowering air velocity. When rain is heavy, water is carried away by gutters on the sides of the motor. Because of this, droplets are not present at the air intakes in any great quantity. The top of the yoke is slanted slightly so that water will drain off.

Cooling air circulates within the motor in this manner: Intake air enters from the sides around the circumference of the yoke, makes a right angle turn at the top, then goes down into the ventilating fans at the ends of the rotor. Ventilation of the rotor and stator cores is normal. Discharged air passes downward from the stator core into the discharge chamber of the motor yoke directly underneath the stator core. From this chamber, air may pass out either end of the motor. During conditions of very strong winds the outside air can also blow completely through this chamber without getting inside of the motor.



AMBIENT AIR passes through this typical outdoor weather-protected motor as shown by the arrows in this diagram.



OUTDOOR WEATHER-PROTECTED motors, more economical than totally enclosed types, are adaptable to most outdoor locations.

Directly under the core iron, an air baffle is provided which protects the bottom of the core during conditions of extremely high winds with rain and dirt.

The motors need no special concrete foundation or base. The foot height, due to the bottom discharge chamber, is a little higher than that of a drip-proof machine. This is an advantage in most cases, since foundations do not have to be as high to meet the requirements of driven machines.

This type motor is designed for use on all major and essential drives, including boiler feed pumps, etc. Both horizontal and vertical designs are built with this protection.

Space limitations influence design

Space is always a major consideration in the modern power plant. Because of this, circulating water pump motors are often placed outdoors. They may be of weather-protected or totally-enclosed fan-cooled design, and either horizontal or vertical. For indoor service drip-proof motors are usually used, although the advantages of totally-enclosed fan-cooled motors frequently dictate their use because of lower maintenance requirements and greater reliability.

Vertical motors use ball bearings for low thrust loads, and oil-lubricated, self-cooled spherical roller bearings for medium thrust loads. For high thrust loads a babbitted, pivoted shoe type self-lubricating bearing is required.

Coal crusher and pulverizer drives usually require high starting torque motors. Generally, they should be totally-enclosed fan-cooled, because of the dirty conditions involved, although this is not always necessary.

Cleaning out motors is a definite part of the program of maintenance. Parts must be readily accessible with openings provided in stator yokes to permit blowing out areas behind the core iron and between the coil end turns. Of course, this work is practically eliminated with enclosed motors, but where the interior of a motor is subjected to the surrounding air and dirt this cleaning out program must be carried on with regularity.

If ambient air is circulated within the motor, it is desirable to have screens over all air intake openings to prevent rags, papers and other material from being drawn into the motors. Such foreign materials can plug up the ventilating ducts and cause overheating. Motors located near aisles and in working areas should be enclosed entirely with guard screens to prevent workmen from accidentally poking ends of pipes or tools into them.

On high speed motors, papers, rags or other material may stick on the outside of air intake screens. This not only interferes with motor ventilation but, by creating a negative air pressure on the inside of the bearing, can cause the bearing oil to be drawn out and spread over the stator winding and other inside parts. Air intake screens must be kept clean.

Protection assures reliability

Extra protection for all motors against electrical breakdown is provided by giving special varnish treatment to the individual stator coils. After the stator is completely wound, the entire stator may be dipped in insulating varnish and baked. This is done at least twice. If the stator cannot be dipped because of size or construction, varnish is poured over the winding end connections. This assures varnish penetration to regions unavailable to brushes or spray guns. Thus the core and stator winding are completely sealed, insuring longer life in this difficult service.

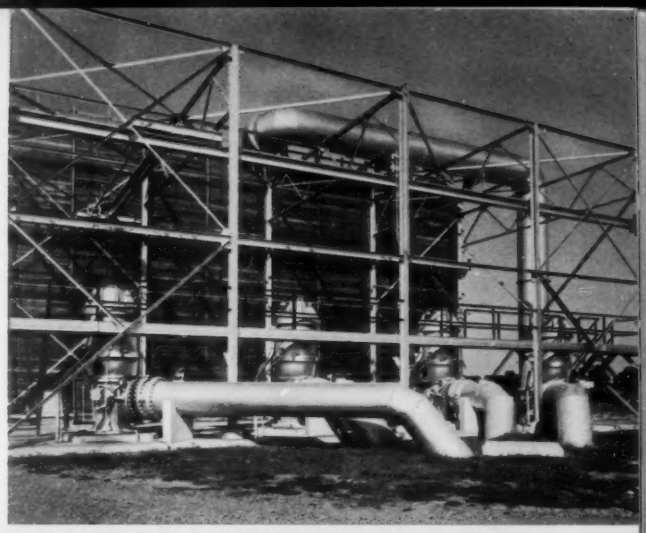
Another important consideration in the operation of motors, especially outdoors, but also indoors where locations are cool or damp, is the provision of some means of keeping motors warm during shut-down periods. This may be done by circulating current through the stator winding or, more commonly, by the use of space heaters. This should be done with any type of motor, open or enclosed.

Interchangeability of motors is always desirable, but the problem becomes rather complicated with a combination of right and left hand drives, such as some draft fan installations. This can be overcome by designing the motors to operate in either direction and by locating the terminal box on the top center line of each motor.

What has been said previously regarding the main motors also applies to the smaller auxiliary drives, such as condensate pumps, primary air fans, stokers, conveyors, etc.

However, many of these smaller motors are not in the "essential auxiliary" class, and more time can be allowed for cleaning and servicing. Here also the question of spares is not quite as important as in the case of the more "essential drives." There are, of course, many more phases of power plant auxiliary drive applications.

In general, the trend has been toward totally-enclosed, fan-cooled and outdoor weather-protected motor enclosures because of their greater service reliability. This trend is receiving further impetus from increased building costs, which make outdoor installations more economically desirable. Because reliability and service continuity are of prime importance, refinements that assure greater dependability are quickly incorporated. Developments will undoubtedly continue along these lines.



MOTORS WITH PROTECTIVE ENCLOSURES for outdoor installations like this are a trend in power plant auxiliaries.

CIRCULATING WATER PUMPS are driven by these 600-hp, 2300-volt, 875-rpm, vertical outdoor type squirrel-cage motors.

DYNAMIC PERFORMANCE

of Synchronous Generator Voltage Regulator

by

H. W. CORY
Asst. Engineer-in-Charge
and
W. F. EAGAN
Control Section
Allis-Chalmers Mfg. Co.

Now, regulator characteristics are predetermined from machine data. Dynamic and static performance are analyzed in the following two articles.

ONE OF THE major problems encountered in designing of a synchronous generator voltage regulator is predicting its stability, or freedom from hunting, before it is placed in operation. Prior to the development of present day techniques for dynamic analysis of feedback control systems, the stabilization of such system was accomplished by "cut and try" methods based on previous experience.

Present day methods of analysis make it possible to arrive at optimum performance more quickly without costly cut and try methods in the field. Regulator stability can usually be designed into the system before it is built. In doing this, all of the requirements of the system must be considered.

The requirements for satisfactory dynamic performance of a synchronous generator voltage regulator system, such as shown in Figure 1, are:

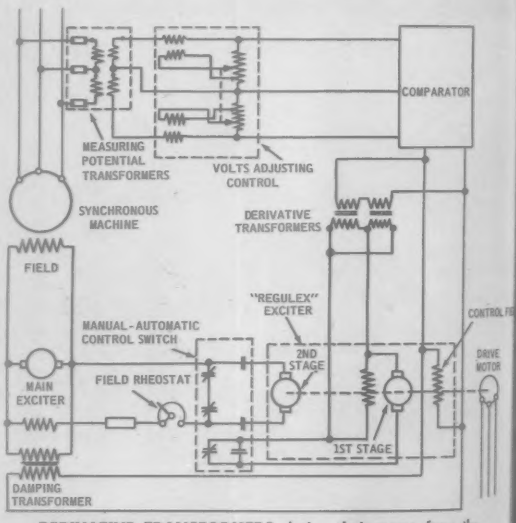
1. High speed of response.
2. Voltage recovery without overshoot or extended period of damped oscillations after a disturbance.
3. No tendency to build up sustained oscillations or hunt.

Periods of operation at low generator excitation are becoming more and more frequent. There is also a trend to use generators of lower short circuit ratio.* The regulator must rapidly boost excitation in the event of sudden load changes or system disturbances in order to prevent loss of synchronism. Ideally, the voltage should recover in zero time with no overshoot.

The first requirement necessitates a high voltage gain and ceiling voltage in the rotary amplifier. These two characteristics create problems in stability.

Field resists sudden excitation change

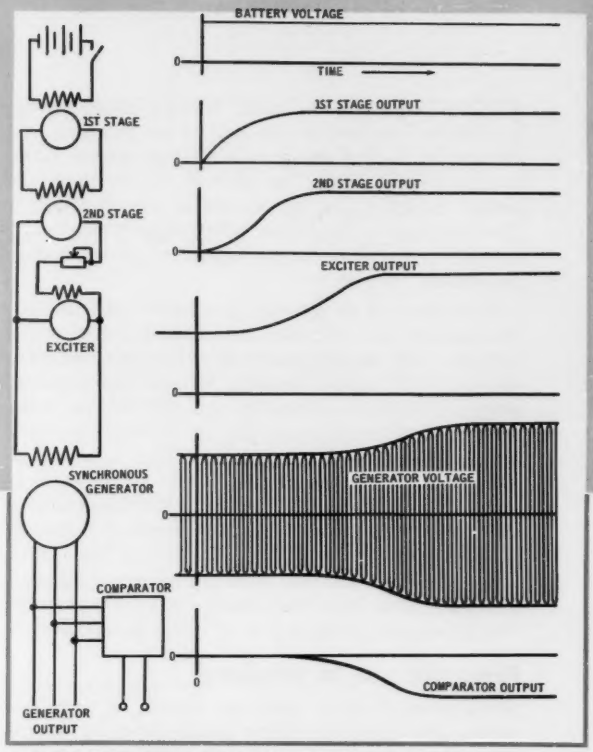
One significant characteristic of rotating machines is the time lag between application of voltage to the field and the build-up of field current or machine terminal voltage. This is due to the inductance of the field circuit. The field circuit has an inherent tendency to resist any change in flux linkages just as the inertia of an automobile tends to resist an increased accelerating torque to the wheels and requires a finite time to reach a new speed. For this reason, it is necessary to provide regulating machines and an exciter capable of delivering voltage several times that required for maximum steady state conditions. This excess capacity "forces" current through the inductive fields and produces a desired increase in output of a succeeding stage in much less time than would be required if a lower maximum voltage were provided. This provision of forcing capacity along with high comparator



DERIVATIVE TRANSFORMERS derive their name from the function they perform. They provide a measure of the rate change in Regulex exciter first-stage output. **(FIGURE 1)**

* *Pull-Out Reserve Controlled and Indicated,* Montgomery, T. B., and Hotson, D. V., Allis-Chalmers *Electrical Review,* 1st Quarter, 1952.

OVERSHOOT is excessive with underdamping (a), recovery too long with overdamping (b), but satisfactory in (c). **(FIGURE 2)**

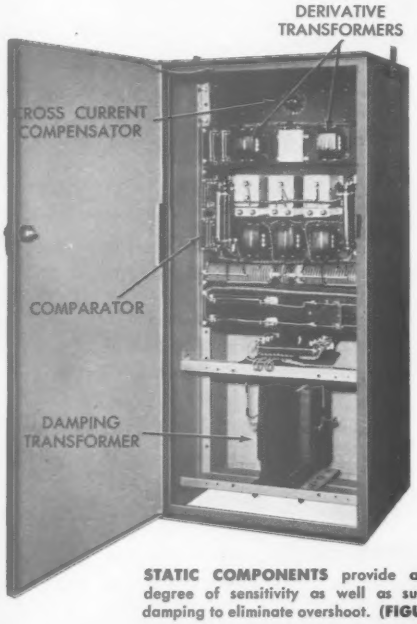


MACHINE FIELD INDUCTANCE delays the battery signal in a regulating system with its feedback loop open. **(FIGURE 4)**

sensitivity produces a high corrective voltage at the exciter field to force generator voltage back to normal in the event of even a small drop in voltage.

Unfortunately these provisions to satisfy the first requirement of a high rate of voltage recovery tend to aggravate the second and third requirements. In trying to overcome the inherent time lags of the field inductances in correcting generator voltage rapidly, the high corrective action tends to cause the voltage to "overshoot" the desired value and thus a corrective action of the reverse polarity is required. This causes the voltage to "overshoot" in the reverse direction. The action described continues and a sinusoidal response occurs. This response may dampen out too slowly or not dampen out at all, resulting in sustained oscillations, or hunting.

Any such tendency is overcome by introducing a signal into the rotating amplifier first stage which is proportional to the rate of change of exciter voltage. Thus as the exciter voltage is rising to correct generator voltage, the comparator signal is balanced out by this rate of change voltage if recovery is too rapid, and would result in "overshoot." Another rate of change signal introduced into the first stage field is that from the output voltage of the first stage. This is positive feedback, or in other words a feedback of a polarity that will speed up the response of the regulating exciters. As the first stage output is increasing, the transformer output adds to the comparator signal and serves to compensate for the time delay inherent in the second stage field.



STATIC COMPONENTS provide a high degree of sensitivity as well as sufficient damping to eliminate overshoot. **(FIGURE 3)**

Rate of change signal used for damping

Excessive rate of change compensation can cause an overdamped or sluggish response. The extremes in manner of voltage recovery are shown in Figure 2.

These rate of change signals are obtained by the use of damping transformers or derivative transformers, such as shown in Figure 3. Any change in primary voltage induces a voltage in the secondary approximately proportional to the rate of change of the primary voltage. One distinctive feature is that the transformer cores are provided with an air gap to prevent saturation due to any steady state value of dc current in the primary.

The effect of inductive lag in the fields of the voltage regulating system with the "feedback loop" opened can be seen in Figure 4. Assuming that no damping transformer is connected in the circuit, that the output for the rotating amplifier is zero, and that the exciter is self-excited to produce rated generator output, the comparator

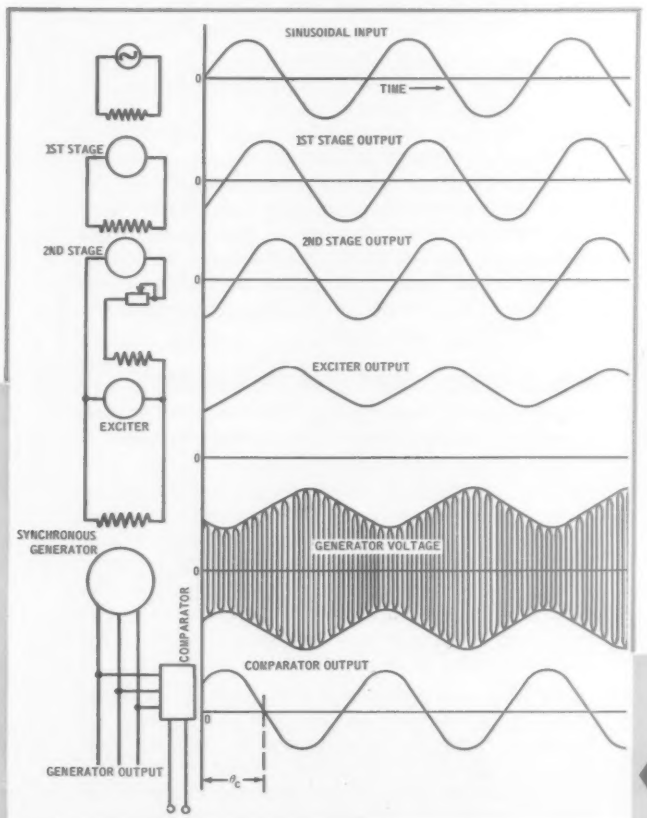
will then put out a zero signal. When a battery voltage is suddenly impressed on the field of the first stage, the resulting build-up of voltage in succeeding stages is shown as a function of time. The effect of the previously described inductive time lag can also be seen in Figure 4. The build-up of voltage in succeeding stages is increasingly delayed in time as the battery "signal" progresses through the system.

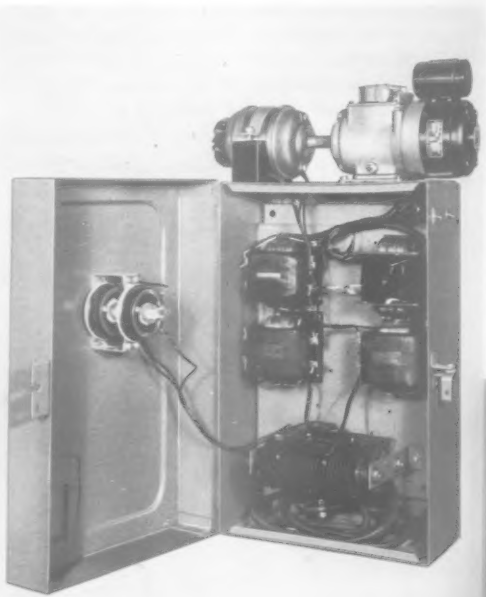
Experience has shown that an unstable regulating system oscillates in a sinusoidal fashion; thus it might be of interest to also study regulator open loop behavior when subjected to a variable frequency voltage. The frequency range of interest for systems of this type will be of the order of 0 to 10 cycles per second. As the sinusoidal signal progresses through the system, it is shifted in phase and changed in magnitude with respect to the input as in Figure 5. This sinusoidal response at low frequencies of a system and its components can be determined analytically in many cases. In cases where analysis is impractical, actual sinusoidal response tests can be run. Figure 6 shows a specially built low frequency sine wave generator with a frequency range of 0 to 12 cycles per second.

Phase shift can be calculated

The amount of phase shift and change in magnitude varies with frequency. These phase shifts are lagging because of the inductive character of the machine fields. The amount of signal phase shift and change in magnitude can actually be calculated from saturation curves and knowledge of the field resistances and inductances. The inductive reactance can be determined for a given disturbing frequency, and the sinusoidal response determined from ac network theory. A vector diagram of various system quantities for a given disturbing frequency showing magnitudes and phase angles with respect to the input voltage is shown in Figure 7. The comparator output is always 180 degrees out of phase with the signal component of generator output voltage, because any increase in generator voltage above that desired must effect a decrease in excitation to return generator voltage to the desired value when the loop is closed. The comparator may also be thought of as containing a fictitious reference voltage, such as a battery. The equivalent circuit is shown in Figure 8. Rectified generator output is compared with the battery, and the amplified difference in voltage is the comparator output. The polarity of this output is in a direction that tends to produce a change in generator excitation which through the feedback circuit will cause a reduction of comparator output as the generator voltage increases.

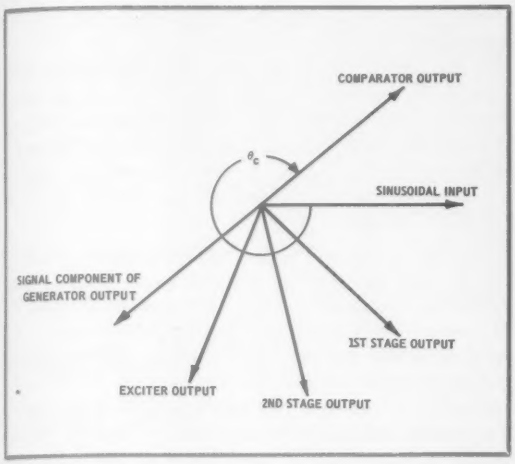
Figures 5 and 7 also show the comparator output lagging input voltage by a large angle θ_c which will further



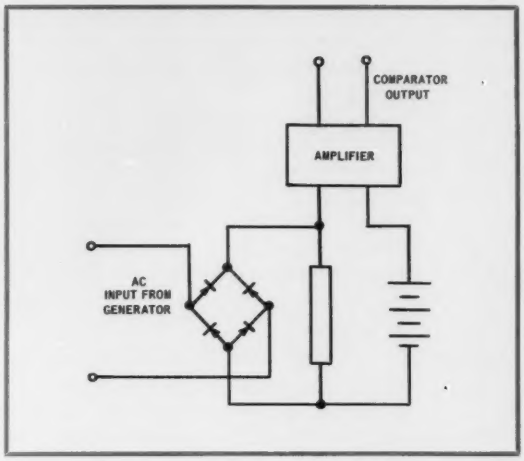


DISTURBANCES VARY in frequency as well as magnitude. This test unit provides a reliable sinusoidal signal for checking phase shift in regulating systems. **(FIGURE 6)**

MACHINE FIELD INDUCTANCE causes a phase shift in the sinusoidal signal as it proceeds through a regulating system having its feedback loop open. **(FIGURE 5)**



SIMPLE VECTORS show phase shift. From the sinusoidal input to the comparator output each stage of amplification causes a lag in phase when feedback loop is open. **(FIGURE 7)**



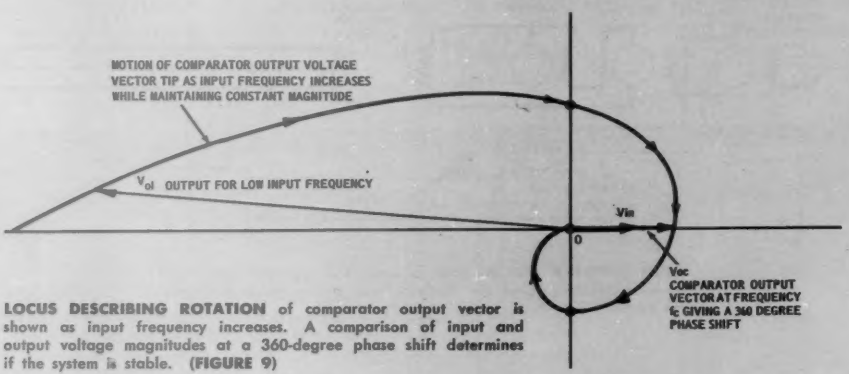
COMPARATOR OUTPUT in this equivalent circuit is the amplified difference between a fixed reference and rectified input signal from the generator. **(FIGURE 8)**

increase as frequency increases. At some value of frequency, this angle will equal 360 degrees. A comparison of output and input magnitudes under this condition determines whether the system will be stable when comparator output is connected to the rotating amplifier.

Analysis is based on sinusoidal signal

The response of the regulating system to a variable frequency sinusoidal disturbance is used to study regulator stability in the following manner. If the sinusoidal input to the rotating amplifier first stage is of an extremely low frequency, the inductive reactances of the machine fields will be low, giving little phase lag as the signal progresses through the system. The signal component of generator output will, therefore, be very nearly in phase with the input voltage. The output of the comparator will be 180 degrees out of phase, as indicated, and the magnitude of the comparator output will be many times greater than system input because of the high regulator voltage gain necessary for accuracy and speed of response, and because of small field reactances at low frequency. This low frequency vector V_{ol} is shown in Figure 9. As the frequency of the input voltage V_{in} is increased and its voltage magnitude kept constant, the comparator output voltage lags more in phase and decreases in magnitude because of the increasing inductive field reactance at increased frequency. The tips of the comparator output voltage vectors for various frequencies describe the locus indicated in Figure 9.

At one value of frequency f_c the output voltage vector V_{oc} is in phase with and greater in magnitude than the input voltage vector in an unstable system. This means that if the comparator output is connected to the first stage field, the regulator will be unstable and oscillate, or "hunt." This is because any slight disturbance will cause a component of the critical frequency f_c to proceed


MOTION OF COMPARATOR OUTPUT VOLTAGE VECTOR TIP AS INPUT FREQUENCY INCREASES WHILE MAINTAINING CONSTANT MAGNITUDE
V_{ol} OUTPUT FOR LOW INPUT FREQUENCY
V_{in}
0
V_{oc} COMPARATOR OUTPUT VECTOR AT FREQUENCY f_c GIVING A 360 DEGREE PHASE SHIFT

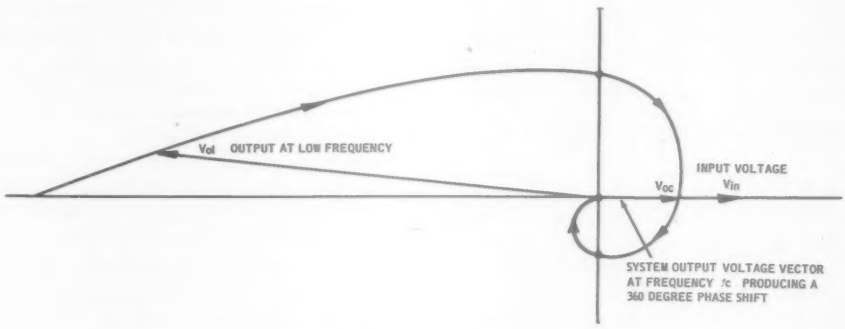
LOCUS DESCRIBING ROTATION of comparator output vector is shown as input frequency increases. A comparison of input and output voltage magnitudes at a 360-degree phase shift determines if the system is stable. **(FIGURE 9)**

through the system and arrive at its origin in phase with and greater in magnitude than the original disturbance. It will again proceed through the system and be further amplified. This action will continue with oscillations building up to a point where they are limited by saturation. The problem is then to provide a means whereby the magnitude of the output vector is less than the input vector at the frequency at which the output is in phase with input. This is done by altering magnitude and phase shift of the sinusoidal signals by the use of the damping and derivative transformers as shown in Figures 10 and 10a.

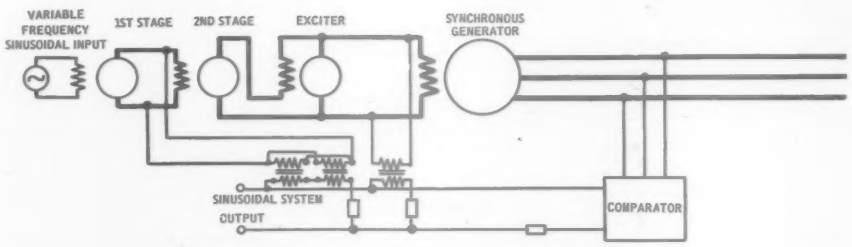
The output of these transformers is added to the comparator output so that their vector sum would give a magnitude less than that of the sinusoidal input at the frequency at which 360 degrees phase shift occurs, thus giving a stable system. The degree of stability or nature of the response, as shown in Figure 2, is determined by the position of the locus with respect to the input voltage vector. Damping transformer output can be modified by changing resistance values in the windings to provide final adjustment in the field.

In this case the sinusoidal components of exciter voltage and the first stage rotating amplifier voltage are introduced through transformers into the comparator output to cause the phase and magnitude relations necessary for stability when the loop is closed. The complete system diagram showing connection of the stabilizing transformers is shown in Figure 1.

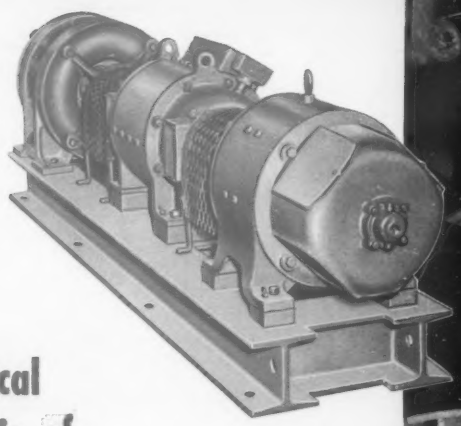
The higher rates of voltage regulator response necessary in present day operating practice have brought about problems in regulator stability. Provision for high speed of response tends to make the regulator oscillate, or hunt, in a sinusoidal manner. Stabilization of these systems can be accomplished by an analysis based on its sinusoidal response. This method of analysis retains a great deal of the physical significance of the actual system for the designer, thereby making it possible to design the stabilizing circuits without a purely mathematical approach.

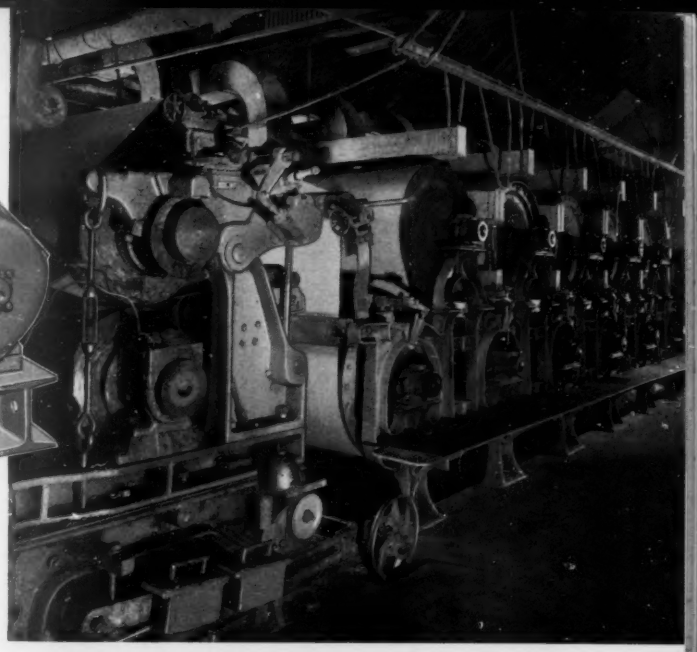


LOCUS DESCRIBING ROTATION of comparator output vector is shown in relation to sinusoidal input voltage as input frequency increases. Comparator output voltage is augmented by damping and derivative transformer output. **(FIGURE 10)**



OPEN FEEDBACK CIRCUIT used to analyze a regulator circuit for dynamic stability. When the feedback loop of this circuit is closed, the system will be stable. **(FIGURE 10a)**





ROTATING REGULATORS now maintain an extremely close control of machinery like this paper drying machine.

Graphical Analysis of Steady State Error Used to . . .

PREDETERMINE REGULATOR ACCURACY

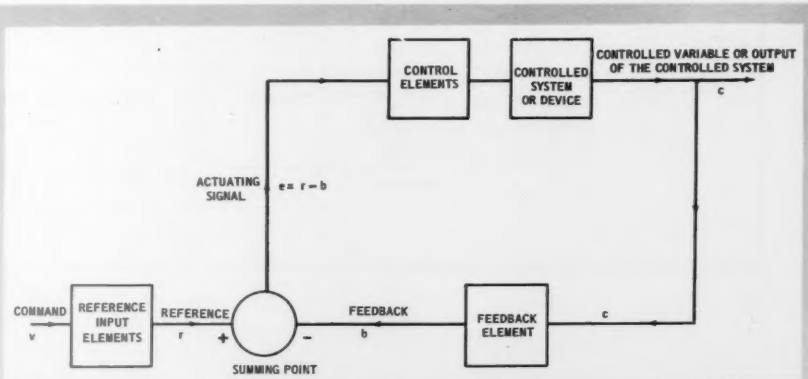
by **W. F. EAGAN**
Control Section
Allis-Chalmers Mfg. Co.

Compensation for gradual changes in ambient conditions can be designed into modern, high amplification regulators.

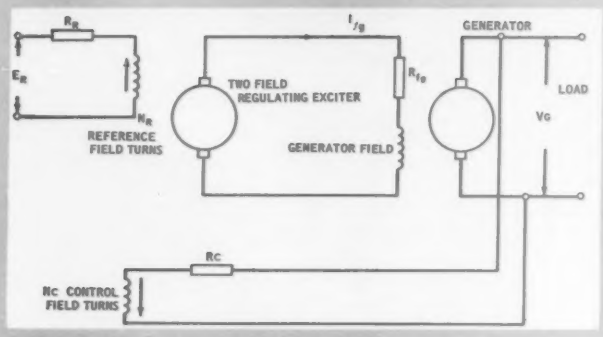
TODAY ALMOST ALL regulators, whether they control speed, voltage, flow, temperature, acceleration or deceleration, or any other important function, are closed cycle systems. Any regulator of either closed or open cycle type are subject to disturbing factors which may cause the regulator to drift slightly from the set or regulated value. The amount of drift is the steady state error.

Figure 1 shows a generalized block diagram of a closed cycle regulator. In this system a feedback signal, which is a measure of the output of the controlled unit, is compared with a reference signal. The difference in strength of these two signals sets the value at which the control element holds the controlled unit. Various disturbances and the inherent characteristics of the components affecting the system make the feedback arrangement necessary.

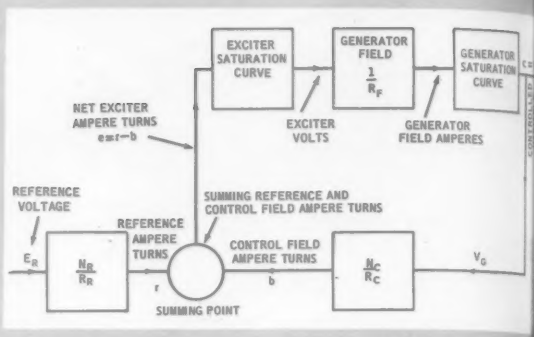
A simple dc voltage regulating system provides a good example of how the steady state error can be determined graphically. In this case the disturbing factors are temperature changes, exciter or generator speed changes, and the loading of components. Other factors, although not disturbances, must be considered when determining accuracy. These factors which are inherent in some system components are hysteresis, mechanical backlash, and friction.



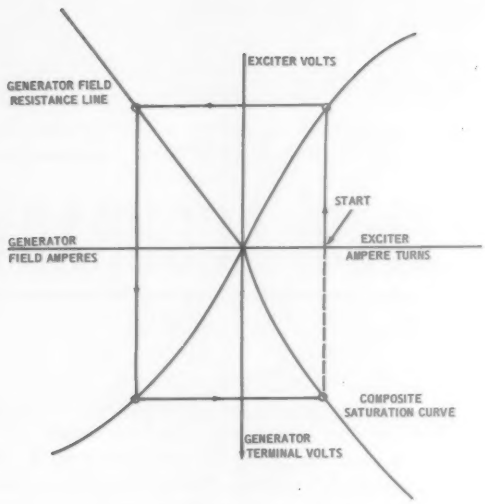
BASIS OF MODERN REGULATORS is the simple control elements shown. A command or controlling signal sets the balance between the reference and feedback signal, thereby setting the value at which the controlled variable will be automatically held. **(FIGURE 1)**



ROTARY VOLTAGE REGULATORS have their command, reference, and feedback signals. **(FIGURE 2)**



REGULATOR CIRCUITS can be reduced to a simple block diagram to show component functions. **(FIGURE 3)**

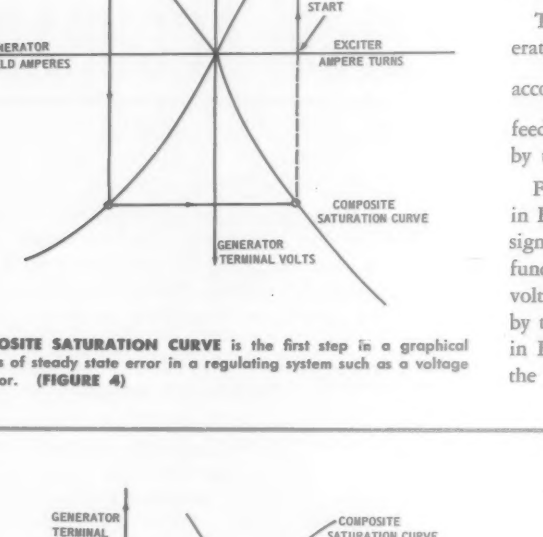


COMPOSITE SATURATION CURVE is the first step in a graphical analysis of steady state error in a regulating system such as a voltage regulator. **(FIGURE 4)**

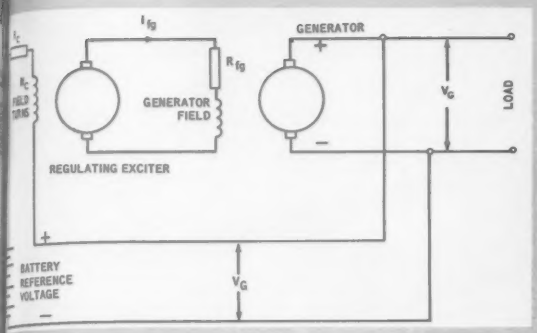
The diagram of a simple dc rotary-type voltage regulator is shown in Figure 2. Here the comparison unit consists of two exciter control fields which are connected so that their ampere-turns buck each other. The reference control field ampere-turns tend to increase the exciter voltage and thereby increase the generator voltage. The feedback control field ampere-turns tend to decrease the exciter voltage.

The controlled variable, which in this case is the generator voltage V_g, is fed back to the feedback control field according to the factor $\frac{N_C}{R_C}$. This factor determines the feedback control field ampere-turns which are produced by the voltage V_g.

Figure 3 shows a block diagram of the schematic shown in Figure 2. The generator voltage V_g and the actuating signal, net exciter ampere-turns, are related by two different functions. One is the static characteristic of the generator voltage in terms of exciter ampere-turns as determined by the components in the top portion of the loop shown in Figure 3. The other is the relation obtained through the bottom portion of the loop.



NET EXCITER AMPERE-TURNS are affected by a change in either reference ampere-turns or control field resistance. Net exciter ampere-turns determine generator terminal voltage. **(FIG. 5)**



FIXED REFERENCE used to directly buck the feedback is assumed for this analysis. **(FIGURE 6)**

Composite curve developed

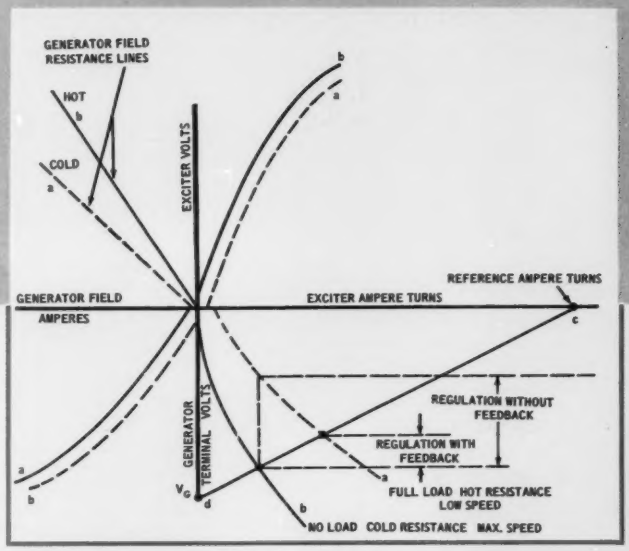
The first characteristic, which is developed in Figure 4, is the composite saturation curve of the exciter and generator. The saturation curve of the exciter is drawn in the first quadrant, and the generator resistance line in the second quadrant. The slope of this line is determined by the ratio of exciter volts to generator field amperes. The generator saturation curve is then drawn in the third quadrant. By projecting points, as shown, the composite saturation curve can be easily constructed in the fourth quadrant. The second relating function between the generator voltage V_g and the net exciter ampere-turns may be expressed by the equation:

$$E_R\frac{N_R}{R_R} - V_G\frac{N_C}{R_C} = \text{net exciter ampere-turns}$$

This function may be represented as a straight line with a negative slope of $\frac{R_C}{N_C}$. The composite curve is replotted in Figure 5. The second function is plotted as a straight line intersecting the horizontal axis at a distance from the origin equal to the reference ampere-turns.

The generator voltage will be maintained at the intersection of the two functions, since the net exciter ampere-turns determine the generator excitation. The intercepting point *a* on the vertical axis is the value of voltage which would serve as a reference if generator voltage were compared directly with a reference voltage and the difference used to excite the system. This circuit is shown in Figure 6.

The effect of loading, temperature changes and speed changes can be seen in Figure 7. Two sets of composite curves were constructed by the method used in Figure 4. The set of curves labeled *a* were plotted under conditions which produce a minimum value of generator voltage. The conditions are maximum loading, maximum temperature, minimum generator rpm and lower hysteresis curve. The set of curves labeled *b* were plotted under conditions which give a maximum value of generator voltage. These conditions are minimum temperature, maximum generator rpm, no load and upper hysteresis curve.

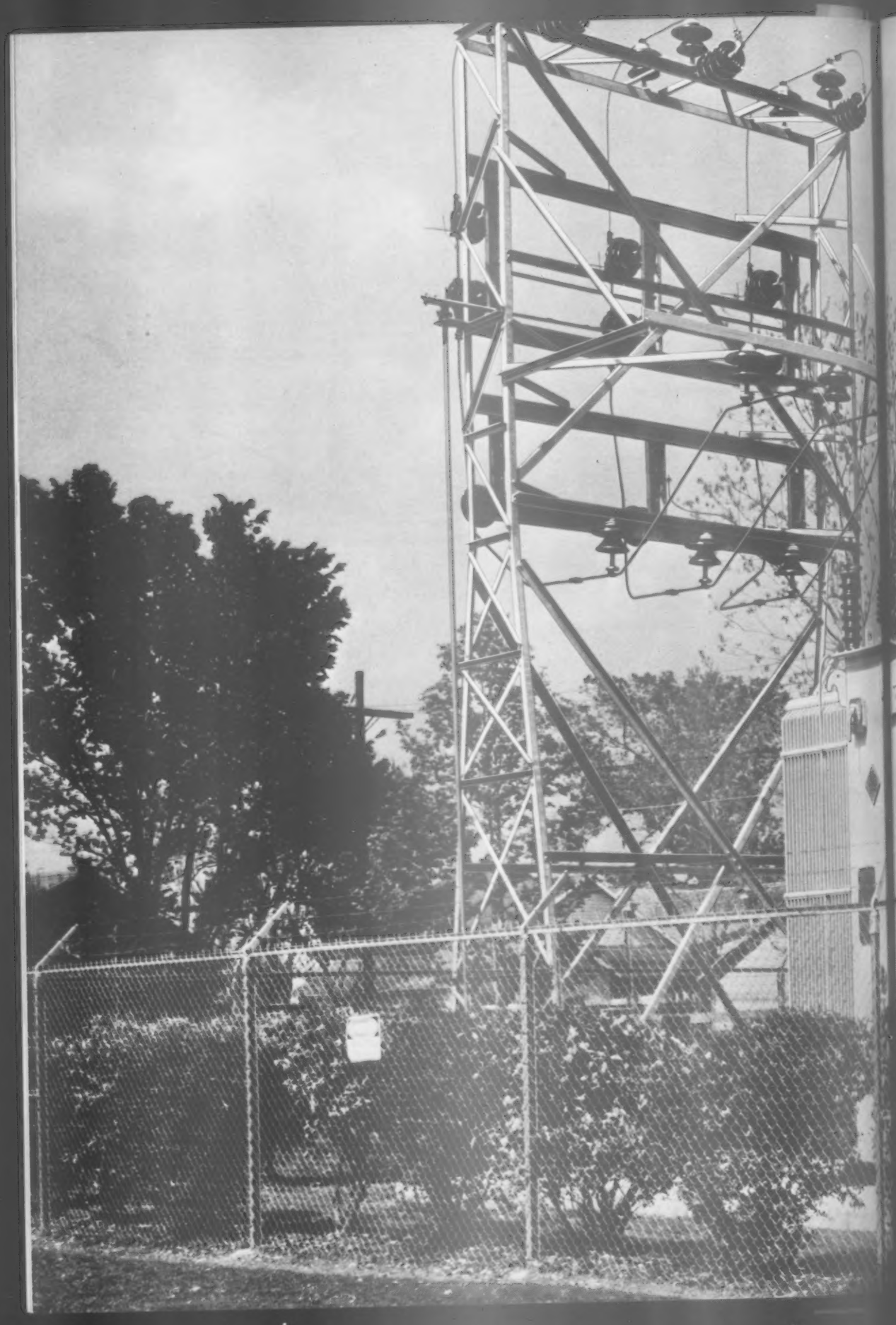


STEADY STATE ERROR due to the influence of such disturbances as temperature is greatly decreased by the use of a feedback type control. **(FIGURE 7)**

The slope of the straight line drawn through the intersecting points *c* and *d* determines the value of $\frac{R_C}{N_C}$. The system reference is determined from whichever intercept applies: *c* for reference ampere-turns, as in the example, or *d* for reference voltage if direct comparison with actual voltage is used as in Figure 6.

The advantages of the feedback type of controller can be seen by comparing the regulation that would result both with and without feedback. The constructions described can also be used to study the effect of any particular type of disturbance on the system. Another conclusion to be gained is that specifications for steady state accuracy should be qualified by the magnitudes of the disturbances, such as temperature, under which the equipment is to operate.

GOOD NEIGHBORS like this 3000-kva multi-circuit unit substation in a Texas city furnish power to entire residential areas. They make modern homes more comfortable, modern home-making more leisurely.



SWITCHGEAR DRAWINGS CLARIFIED

Key to Better Service!

by **R. STOWE**
Switchgear Section
Allis-Chalmers Mfg. Co.

Join the author while he goes through a set of switchgear drawings explaining how to find specific information.

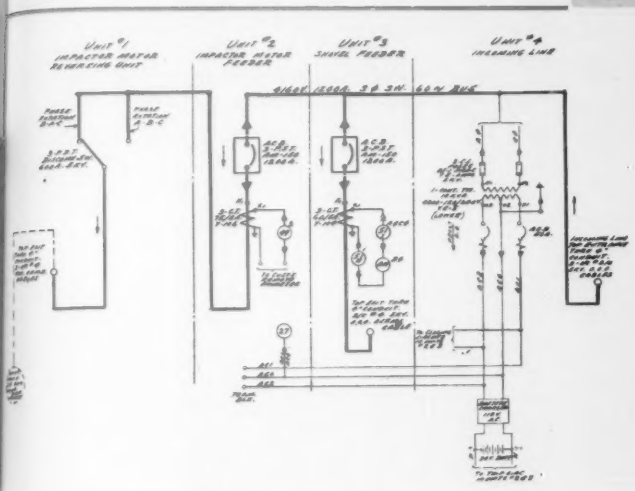
IN THE PAST, drawings that show the many devices and numerous electrical connections of a switchgear group have often been complex and difficult to use. Through the years, however, a systemized series of drawings has been developed to facilitate a clearer conception of the equipment.

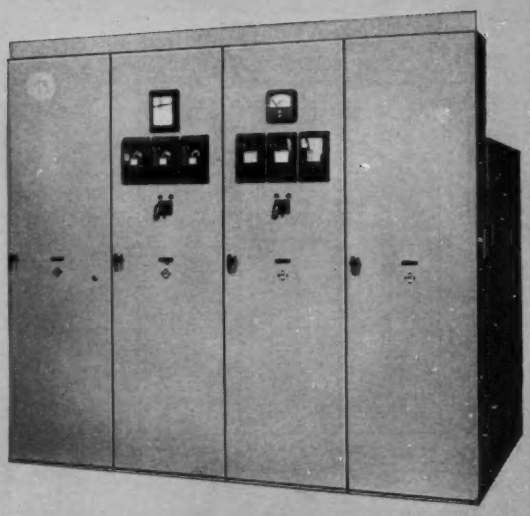
Each drawing in this series has a definite and singular purpose. In addition, these drawings complement each other to give a complete, yet easily understandable picture of any switchgear installation. By understanding the function of each drawing, a clear visualization of the equipment can be obtained even before it is manufactured.

Usually, there are ten types of drawings in this systemized series. These are divided into two groups: One group relates to the physical installation; the other, to the electrical functions and circuits.

Not all of the switchgear drawings for a specific job can be made up at one time. Rather, drawings are evolved through a series of checks to make sure that the finished switchgear will provide exactly the functions that are required.

During preliminary stages, specifications are prepared and a single line sketch is made indicating required electrical devices and functions. From this sketch and the specifications, the single line diagram is prepared. It gives a general outline of all the equipment furnished in





THIS SINGLE LINE DIAGRAM indicates the electrical circuits and devices that are contained in the group of switchgear shown at right.

GENERAL ARRANGEMENT and floor plan drawings give overall size and details of channel mounting, cable entrances, shape, etc.

a group of switchgear units and indicates electrical connections of the principal switchgear components. However, it does not indicate physical location of these devices.

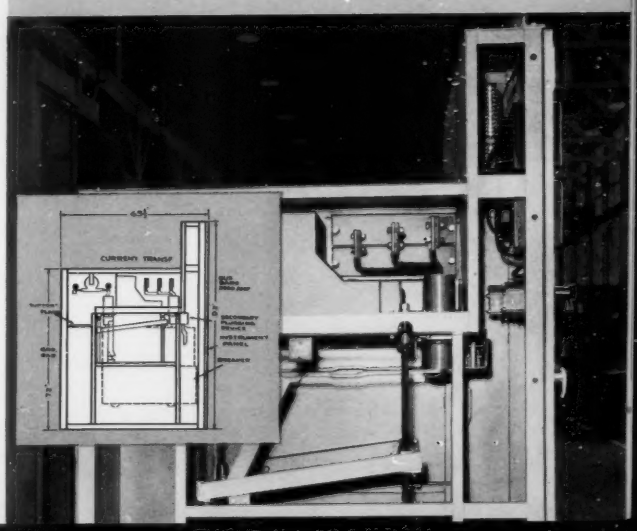
Information contained on the single line diagram includes: ratings of circuit breakers, switches, potential and current transformers; types and functions of relays; connections of instruments and meters; ratings of resistors and reactors; size and number of primary cables, etc.

Size and shape depicted

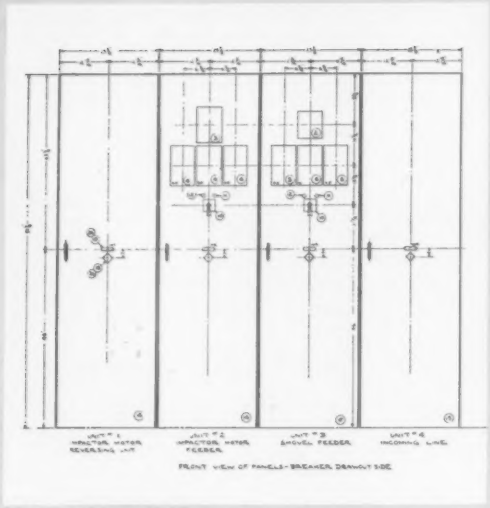
The general arrangement and floor plan diagram indicates the physical size and shape of the switchgear group. Besides showing the overall dimensions, location and size of primary and secondary wiring openings as well as data for preparing the floor are given. The sill channel mounting drawing, furnished in conjunction with the general arrangement drawing, includes a cross-section view showing the preferred methods of installing the mounting channels in the floor. Correct location of sills and floor openings assures easy installation when the switchgear arrives at the site.

Side views

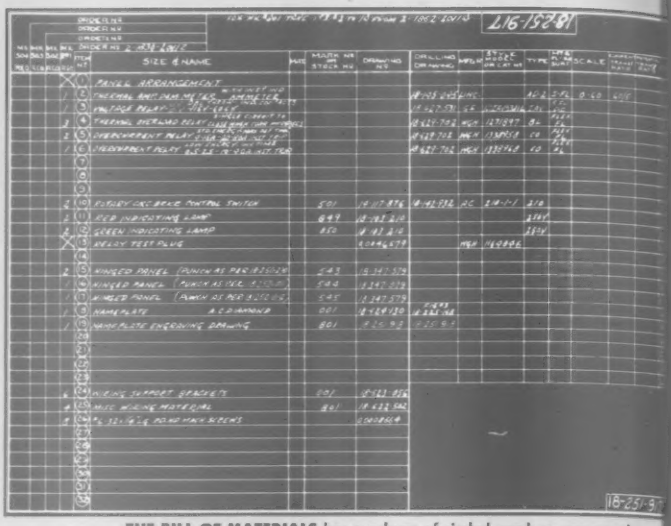
So that the exact location of major equipment items within the switchgear units can be ascertained, a separate side view drawing for each unit is made. Where the major features of several units in a group are duplicated, the same side view applies to all. Side views, general arrangement, floor plan, and sill channel drawings all relate to the physical structure and should all be at hand when checking or discussing a switchgear group. Together, these drawings contain all information necessary to prepare the installation site.



SIDE VIEW DRAWINGS give a photographic concept of the location of major equipment items within each switchgear unit.



PANEL ARRANGEMENT gives front view of all panels in the group. Each panel mounted item is located by dimension, designated by a circled number.



THE BILL OF MATERIALS has a column of circled numbers corresponding to circled numbers on the panel arrangement drawing. All items are designated as to size, style, drawing number, etc.

Panel arrangement

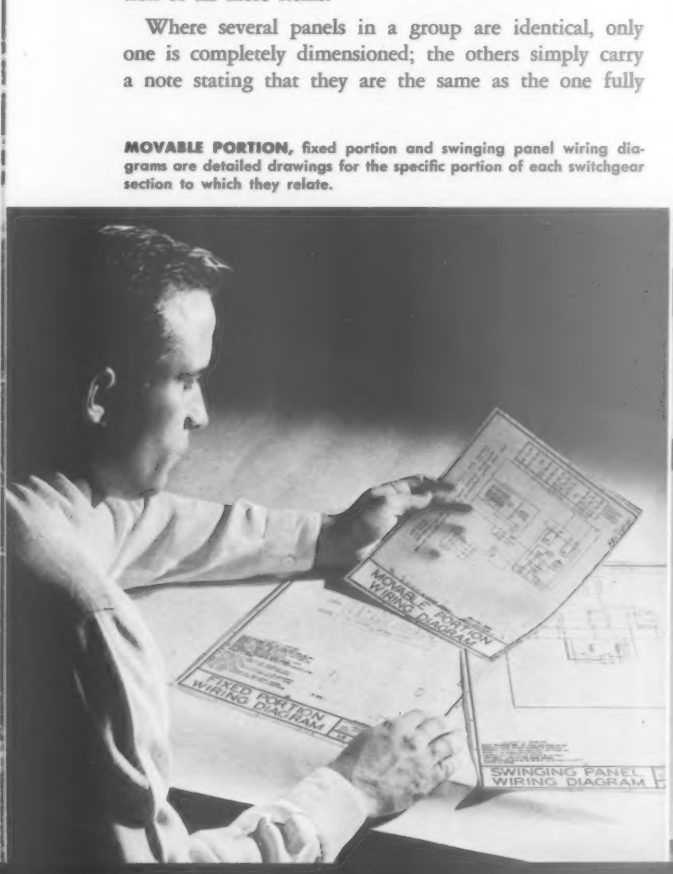
The panel arrangement drawing gives exact location of all items on the switchgear panels. The exact dimensioned locations of all equipment mounted on every panel of the switchgear group is indicated. Each item shown on a panel is designated by a circled number which corresponds with the same item on the bill of material. The bill of materials, sometimes shown on the panel arrangement and sometimes on a separate drawing, gives a detailed description of all these items.

Where several panels in a group are identical, only one is completely dimensioned; the others simply carry a note stating that they are the same as the one fully shown. This drawing is usually checked before manufacture begins, to make sure that panel mounted devices are in the best possible position for convenient operation.

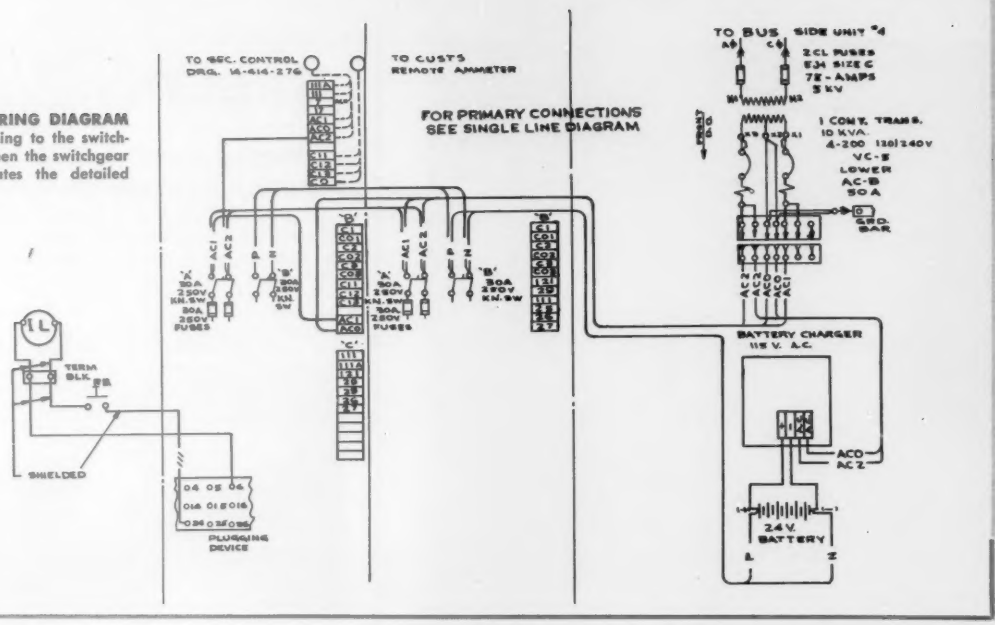
Wiring diagrams simplify connections

Several of the drawings are wiring diagrams. They give the user a complete picture of the electrical aspect of the switchgear group and are guides to correct electrical installation. First in importance is the master wiring diagram. It shows external secondary connections, all of the wiring interconnections between units, and the connections necessary between groups if the gear was divided to facilitate shipping.

MOVABLE PORTION, fixed portion and swinging panel wiring diagrams are detailed drawings for the specific portion of each switchgear section to which they relate.



SWITCHGEAR GROUP with the panel of one unit open and the movable portion withdrawn to show the portion covered by each detailed wiring diagram.



THE MASTER WIRING DIAGRAM shows external wiring to the switchgear, wiring between the switchgear units, and correlates the detailed wiring diagrams.

Master wiring diagram

The master wiring diagram also tabulates the drawing numbers of all section diagrams, identifying them as to their proper unit and section number. These section diagrams, which should be at hand to get a complete picture, include: movable portion wiring diagrams, swinging panel wiring diagrams, and fixed portion wiring diagrams. Where terminal blocks, fuse blocks, knife switches, and other devices are shown on both the master wiring diagram and the fixed portion diagram, they are properly identified to point out these duplications.

Fixed portion diagram

Fixed portion wiring diagrams show the complete wiring within each individual switchgear unit, except for the wiring on the panel. A separate fixed portion diagram is made for each unit in a group. Where two or more units have duplicate wiring, the same diagram is used for all such units. Because most of the devices are mounted on the panel, the fixed portion diagram indicates only such items as connections between fuses, knife switches, current transformers, terminal blocks, and plugging device for the movable portion.

Swinging panel diagram

Connections to the terminal blocks of all devices mounted on the panel are shown on the swinging panel wiring diagram. Complete wiring diagrams for each individual panel make it possible to wire each panel separately and completely before mounting it in the unit. The arrangement of equipment on the panel wiring diagram corresponds as nearly as possible to the position on the panel arrangement as viewed from the rear of the panel.

Movable portion

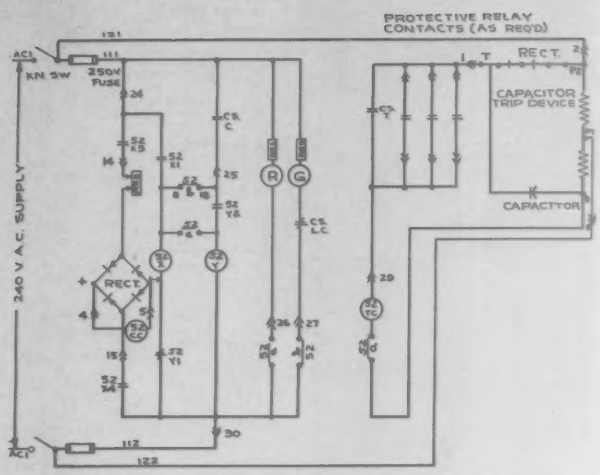
The movable portion wiring diagram shows connection to the secondary plugging device of all the equipment mounted on the movable portion. This includes control relay, number and type of auxiliary switches, trip coil, closing coil, etc. Like the panels, each movable portion may be completely wired by using its individual diagram. When movable portions in a group of switchgear are identical, the same diagram is used for all.

Circuit breaker control schematic

If, for some reason, it is necessary to trace the circuit breaker control circuit, the circuit breaker control schematic diagram simplifies the procedure. On this drawing, all electrical devices are shown according to their functions. Without jumping from one drawing to another, the electrical function of every part of the control circuit can be determined.

The devices indicated by symbols on the schematic diagram are actually mounted in several different places, as shown in detail on the various section diagrams. For example, the control switch and colored lights with resistors are mounted on the panel; the knife switch, fuses, rectifier, and resistor are in the fixed portion, while the closing coil, trip coil, capacitor trip device, circuit breaker control relays and auxiliary switches are in the movable portion. Combining all of these devices and connections on one drawing makes it very easy to see how the complete control scheme operates. All symbols shown are identified, and notes explain significant features of the control scheme. Each device carries the same symbol number on every drawing where it appears.

Through a clear conception of switchgear drawings,



CIRCUIT BREAKER CONTROL SCHEMATIC diagram makes it easy to trace the circuit breaker control circuit. Devices are located on this schematic according to their function.

quicker installation of equipment is facilitated. Knowing the type of information contained on each drawing of the systemized series assures faster and more thorough inspections, better service from the equipment. More detailed information on the individual devices and component parts of the switchgear units is contained in instruction books that accompany the switchgear.

INSTRUCTION BOOKS, supplied with the switchgear, contain detailed information on the various individual components and breakers within each switchgear group.

New Products

New Weather-Protected Motor for Outdoor Installations Is Announced

A new motor which carries protection much further than splash-proof design has been developed.

Its enclosure is designed to keep wind-driven heavy moisture, dust and dirt out of the windings. Intake air velocity has been reduced to less than 600 feet per minute so that heavy rain particles cannot be drawn into the motor. Air moves vertically upward through side intakes into a greatly expanded air space, further lowering velocity.

Rain gutters on the sides at the air intakes drain to the ground through pipes. During periods of extremely heavy rain, simulated in this test, water running down the sides of the motor drains away before droplets accumulate in any great quantity at the air intakes.

Air intakes are high above ground level to prevent dust and dirt from blowing into the machine during dry weather. Screens over the intakes keep paper, leaves and large particles from entering. Air filters can be installed to give still greater protection.

This weather-protected motor, also pictured on page eight, is available in the full range of ratings required for major auxiliary drives, including boiler feed pumps.

New Mill Contactor With Arc Centering Device Has Increased Contact Life

A new line of heavy-duty, single-pole, dc contactors, designated as Type 260, has been developed for use on rolling mill controls, mill auxiliaries, cranes, hoists, and related equipment. Both normally open and normally closed types are available.

Built for long contact and arc chute life, this new contactor is designed to speed routine inspections and facilitate rapid replacement of wearing parts.

Contact life is extended greatly by a new principle of arc interruption which reduces contact burning by speeding extinction. Metal segments, insulated from each other by arc-resistant asbestos cement compound arc chute walls, speed arc extinction by acting as individual blowout structures. High density forged copper contacts have a pronounced rolling action and take arcing on tips to prolong contact life.

Contacts can be easily and quickly replaced by loosening one screw, slipping out the worn contact, and inserting the new one.

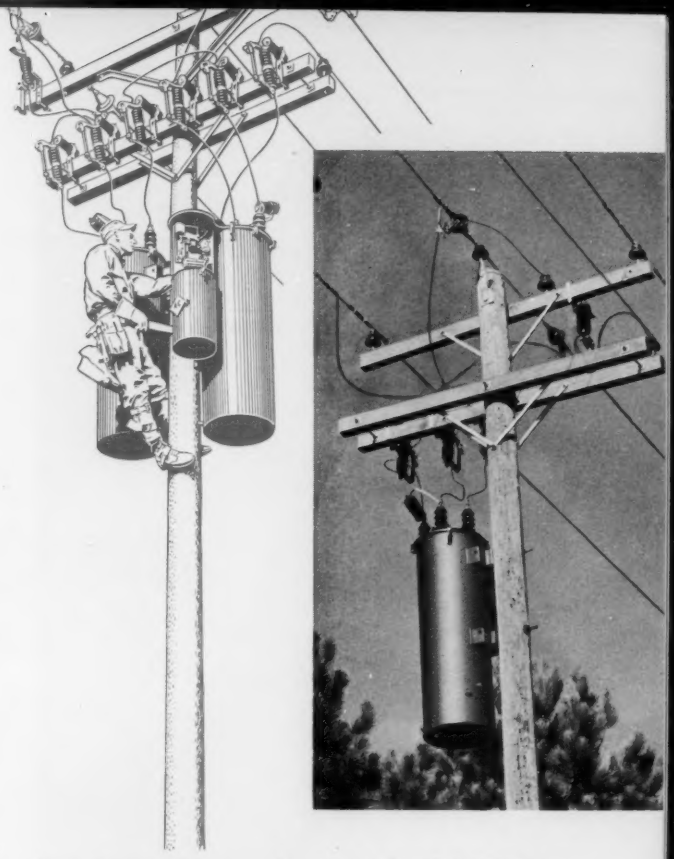
This new contactor, with or without electrical auxiliary interlocks, has been developed in ratings of 600, 300, and 150 amperes at 600 volts.

MORE INFORMATION about these products can be obtained by writing Allis-Chalmers ELECTRICAL REVIEW Milwaukee 1, Wis.

CLOSED DELTA OPERATION

of Single-Phase Step Type Regulators

by **C. W. NIELSEN**
Transformer Section
Allis-Chalmers Mfg. Co.



Today, more distribution type regulators are being connected in closed delta to gain a wider range of regulation.

WHEN SINGLE-PHASE regulators are used on three-phase lines, they are normally connected in wye on a four-wire system or open delta on a three-wire system. At times; however, it is advantageous to connect three single-phase regulators in closed delta. The addition of the third regulator does not increase the three-phase circuit kva, but it does increase the range of regulation by approximately 50 percent, that is, to approximately ± 15 percent regulation with ± 10 percent regulators.

The kva rating of a single-phase regulator in a three-phase circuit carrying a specified load is determined by the percent voltage regulation. For open-delta operation, shown in Figure 1, the series winding of each regulator carries line current, and the kva rating of each single-phase unit is as follows:

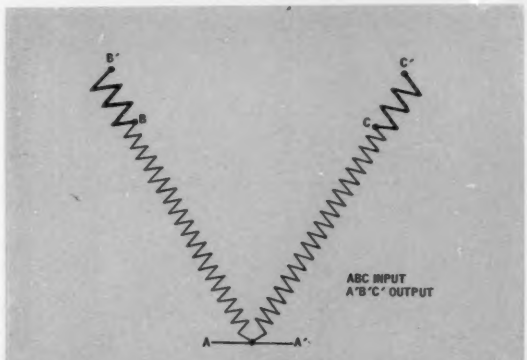
$$\text{kva (reg.)} = \frac{\text{percent regulation x kva (3-phase circuit)}}{100 \times \sqrt{3}}$$

Thus for 10 percent regulation of a circuit carrying 1500 kva,

$$\text{kva (reg.)} = \frac{10 \times 1500}{100 \times \sqrt{3}} = 86.7$$

When three single-phase regulators are connected in closed delta on a three-phase line, each regulator carries line current also. Thus each regulator must be the same size as for open-delta operation. For a circuit of 1500-kva capacity, each regulator must be at least 86.7 kva in size. At positions other than neutral the circuit kva may be increased slightly, since the line current is made up of current from the series and exciting windings. This increase is approximately 5 percent at maximum raise position. Since there is no increase at the neutral position, this change in kva cannot be used for general application.

As mentioned before, closed-delta operation of three single-phase regulators gives an increase of 50 percent in the range of regulation over open-delta operation. The



TWO SINGLE-PHASE distribution type regulators are usually connected in open delta on three-phase, three-wire systems. The line current flows in sections $B - B'$ and $C - C'$. **(FIGURE 1)**

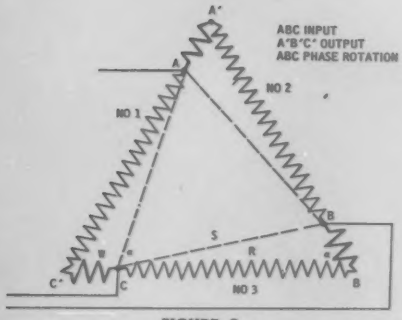


FIGURE 2

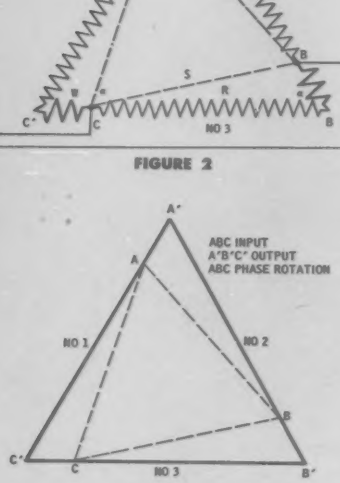


FIGURE 3

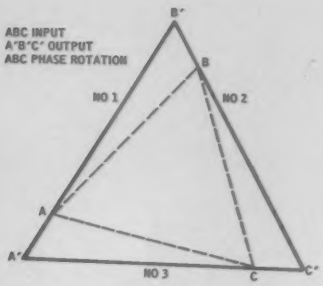


FIGURE 4

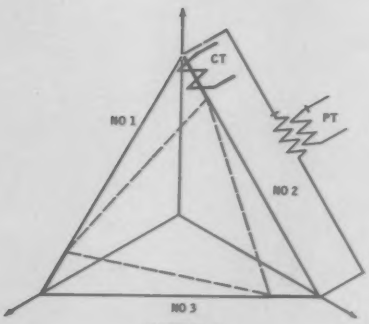


FIGURE 5

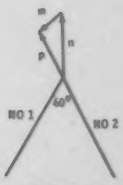


FIGURE 5a

vector diagram of three closed-delta connected single-phase regulators in the maximum boost position is shown in Figure 2.

Let $R = C\text{-}B'$ (voltage of exciting winding of reg. No. 3)

$X =$ percent voltage regulation of each regulator

$V_2 =$ output voltage $C'\text{-}B'$

$V_1 =$ input voltage $C\text{-}B$

$W = C'\text{-}C$ (voltage of series winding of reg. No. 3)

$\alpha = 60°$

Then

$$V_1^2 = (R - W\cos\alpha)^2 + (W\sin\alpha)^2$$

$$W = RX$$

Substituting

$$V_1^2 = R^2(1 - \frac{X}{2})^2 + \frac{3}{4}R^2X^2$$

$$V_1 = R\sqrt{1 - X + X^2}$$

$$\text{Now } V_2 = R + W = R(1 + X)$$

$$\text{Then } V_1 = \frac{V_2}{X+1}\sqrt{X^2 - X + 1}$$

$$\text{And } V_2 = V_1\frac{X+1}{\sqrt{X^2 - X + 1}}$$

$$\text{If } X = 5\%, V_2 = V_1(1.075+)$$

$$\text{If } X = 10\%, V_2 = V_1(1.1531+)$$

Regulators lead or lag

Regulators may be connected either leading, as shown in Figure 3, or lagging, as shown in Figure 4. With the leading connection the current in the series winding of each regulator leads the voltage across that regulator when the load is at 100 percent power factor. The lagging connection has a similar meaning. There are certain advantages to each connection.

Three single-phase regulators connected in closed delta must be used only on radial feeders, for the output voltage has a phase shift of approximately ± 5 degrees when plus or minus 10 percent regulators are used.

When three single-phase regulators are connected as in Figure 3 or 4, the current in the line of each regulator at 100 percent power-factor load leads or lags the voltage across its potential transformer by 30 degrees. For correct line-drop compensation, the current in the compensator circuit should be in phase with the control voltage at 100 percent power factor. This phase shift may be made without complex phase shifting circuits that might lessen the reliability and accuracy of the control equipment. The combination vector and schematic diagram in Figure 5 shows current and potential transformer connections.

Where the three regulators are located close together at a substation, they may be interconnected as shown in Figure 6 for leading connections, or for lagging connections, as shown in Figure 7. These interconnections shift the current vector 30 degrees by adding a current vector

from an adjacent phase. The magnitudes of the vectors are adjusted within the auxiliary current transformer.

Vector n, Figure 5a, is the line current of regulator No. 2. Vector m is the line current of regulator No. 1. Vector P is the resultant current which flows in the line-drop compensator of regulator No. 2 and is in phase with the voltage across regulator No. 2 at 100 percent power-factor load.

Where the single-phase regulators are located some distance apart, as with pole type or distribution regulators, the phase shift may be taken care of by setting the resistance and reactance values of the line-drop compensators, not with the actual values of line resistance and reactance drop, but with calculated values which take care of the phase shift.

Let R and X = the resistance and reactance drop of the line.

R_1 and X_1 = the resistance and reactance compensator setting volts for the lagging connection.

R_2 and X_2 = the resistance and reactance compensator setting volts for the leading connection.

$$\text{Then } R_1 = .866R - .5X \qquad R_2 = .866R + .5X$$
$$X_1 = .5R + .866X \qquad X_2 = .866X - .5R$$

Compensation calculated

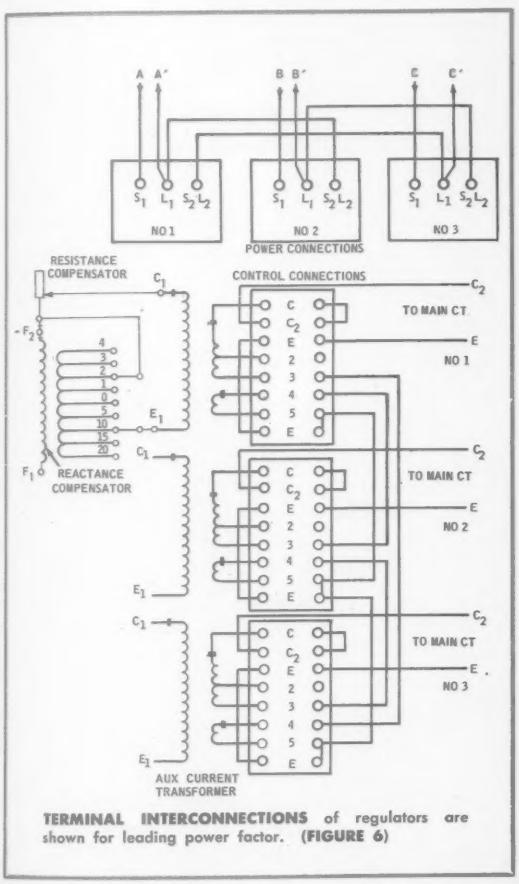
The table, Figure 8, makes it possible to select the correct compensator setting volts without making individual calculations. For negative values the compensator must be reversed. This may be done if the reactance compensator has two windings.

1. To obtain negative values of X reverse the leads on the untapped winding of the reactor.
2. To obtain negative values of R reverse the current transformer leads and reverse the reactor as in 1 to make X positive.

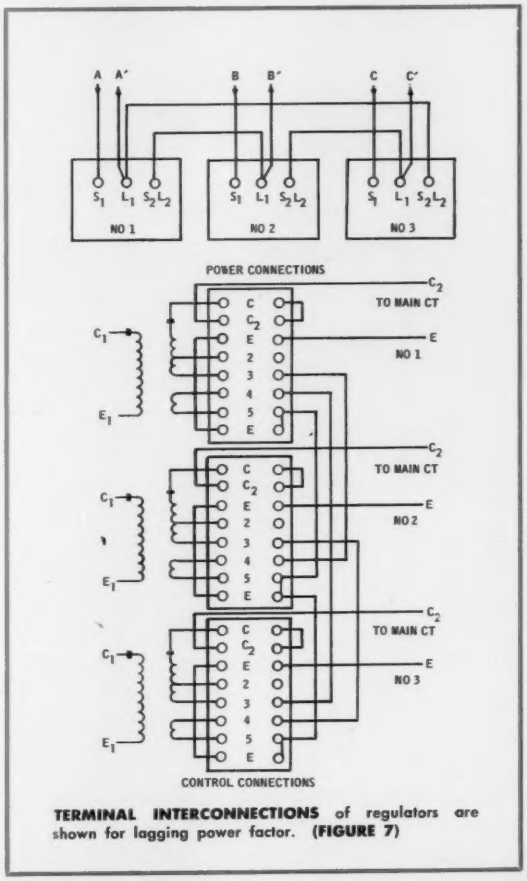
By selecting lagging or leading connections for specific cases, it is possible to obtain all positive values of compensator setting volts.

With leading connections as shown in Figure 3

If $\frac{X}{R}$ is equal to or greater than $\frac{1}{\sqrt{3}}$, all calculated values of resistance and reactance compensator setting volts will be positive.



TERMINAL INTERCONNECTIONS of regulators are shown for leading power factor. **(FIGURE 6)**



TERMINAL INTERCONNECTIONS of regulators are shown for lagging power factor. **(FIGURE 7)**

With lagging connections as shown in Figure 4

If $\frac{X}{R}$ is equal to or less than $\sqrt{3}$, all calculated values of resistance and reactance compensator setting volts will be positive. Figure 8 shows the separation of these areas.

For closed-delta operation of single-phase regulators the same size units must be used as in open-delta operation. The percent regulation with closed-delta operation is approximately 50 percent greater than with open-delta operation.

Regulators may be connected either leading or lagging. Two methods have been presented for obtaining correct operation. One uses interconnecting control wires; the other may find application where the regulators are some distance apart.

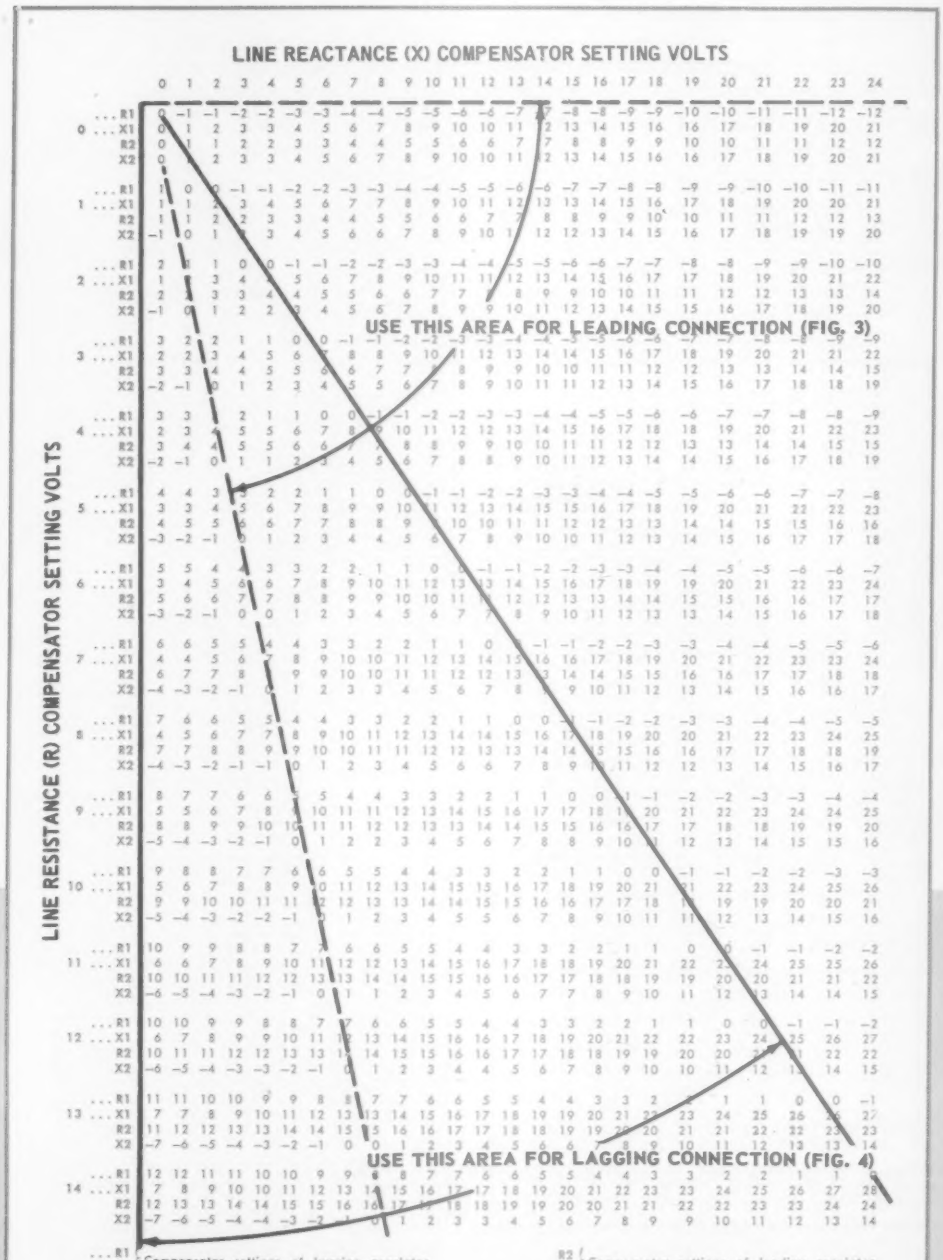

LINE REACTANCE (X) COMPENSATOR SETTING VOLTS
LINE RESISTANCE (R) COMPENSATOR SETTING VOLTS
USE THIS AREA FOR LEADING CONNECTION (FIG. 3)
USE THIS AREA FOR LAGGING CONNECTION (FIG. 4)
Compensator settings of lagging regulator
Compensator settings of leading regulator

FIGURE 8

SIX THOUSAND BARRELS of cement are produced each day in an Iowa plant by two kilns powered through this electrical equipment. The high voltage starter at left controls the 725-hp, three-phase, 900-rpm synchronous motor driving a dc generator. Switchgear then distributes the direct current to drive motors on the kilns, and to excite the fields of synchronous motors in the mill plant.

Paralleling

LOAD RATIO CONTROL TRANSFORMERS

by **W. C. SEALEY**
Engineer-in-Charge
Transformer Engineering
Allis-Chalmers Mfg. Co.

Here's help in selecting control circuits for tap changers.

TRANSFORMERS ARE OFTEN connected in parallel if the load increases beyond the capacity of a single unit. Sometimes two or more transformers are paralleled to permit continuous operation of a station even when one transformer is removed for inspection, maintenance or service during a light load period. When two or more units are connected in parallel, it is possible to reduce light load period losses by taking one unit out of service.

Transformers are also connected in parallel on network systems where the units and the loads are distributed geographically. In this manner, all units help supply an increased load at one location. In addition, any one of the paralleled transformers can be taken off the line without interrupting power continuity.

Whatever the reason for paralleling transformers, if the paralleled transformers are to divide a given load properly, they must have approximately the same percent impedance and voltage ratio. If these transformers are provided with automatically controlled tap changers to regulate the voltage, provision must be made in the control circuits to keep the ratios of the two transformers approximately the same.

Control circuits balance loads

While the control circuits employed for this purpose may seem complicated, the general principles underlying their operation are relatively simple.

With the exception of the electrical interlock method, all the schemes utilize the difference in currents between transformers to actuate the tap changers for proper division of load. The control operates to decrease the difference in current between units. The transformer with the highest current will have its current reduced. The transformer with the lowest current will have its current increased. This process is continued until the currents carried by the paralleled machines are approximately equal. This type of operation is secured by means of control circuits which include voltage control relays and line-drop compensators as essential elements.

PARALLELED TRANSFORMERS like these must have their control circuits properly connected to divide load properly.

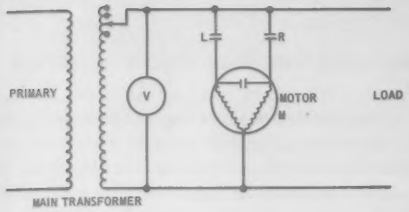
The output voltage of a load ratio control transformer may be kept constant by the use of a voltage relay connected across the secondary terminals. Figure 1 shows a simplified load ratio control circuit. The voltage relay *V* controls the raise and lower contacts *R* and *L* which control the tap changer motor *M*. The use of voltage integrators, time delay relays, auxiliary relays, or auxiliary potential transformers in the circuit does not change the fundamental principles of operation.

When the power transformer is located at some distance from the load center, a line-drop compensator is used to produce the same effect as pilot wires running from the load center to the voltage relay. A line-drop compensator consists of a resistor and reactor connected in series with the voltage relay coil, as shown in Figure 2. A current proportional to the line current is circulated through a portion of this resistance and reactance. This current is obtained from a current transformer connected in series with one line. It produces a voltage drop in series with the voltage relay, which can be made equivalent to the voltage drop in the line from the power transformer to the load. The voltage control relay regulates for a voltage which is equal to its no-load voltage plus the voltage produced by the circulating current in the line-drop compensator.

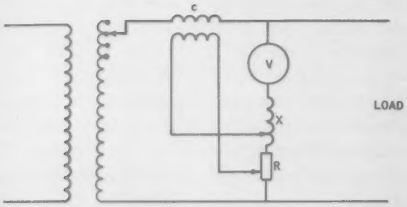
Compensation affects circulating current

When two transformers are paralleled, their secondary windings are solidly connected together. Consequently, a change in ratio of one transformer results in equal changes in the output voltage of both transformers.

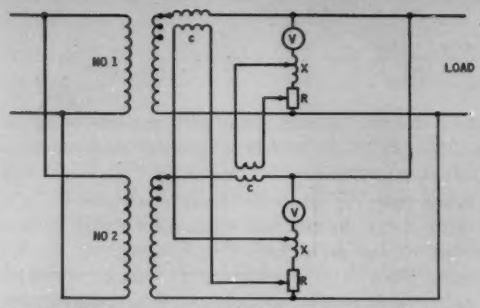
If the circuit diagrammed in Figure 1 is used for individual voltage control of each of two paralleled transformers, constant voltage will be maintained. However, the tap changers of the two transformers may be on widely different taps, with the result that unequal currents will



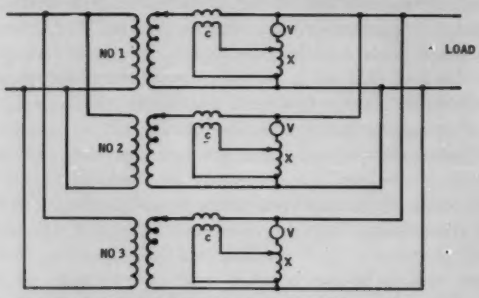
SIMPLIFIED CONTROL CIRCUIT indicates voltage relay which closes contacts to operate tap changer. **(FIGURE 1)**



ONE MACHINE runs to maximum raise position, the other to maximum lower, if this circuit is used. **(FIGURE 2)**



CROSS-CURRENT COMPENSATION, connecting the current transformer of one machine to the compensator of the other, divides the load of two transformers properly. **(FIGURE 3)**



TWO OR MORE TRANSFORMERS will divide load proportionally without interconnections if reversed reactance compensation is used, but voltage falls as load increases. **(FIGURE 4)**

be carried by the two units. Because the currents in the two transformers may be out of phase, both transformers may be overloaded even with zero load on the transmission line to which they are connected.

If the circuit indicated in Figure 2 is used for voltage control of each of two paralleled transformers, one machine will run to the maximum raise position while the other will run to the maximum lower position. This action occurs because when one unit is on a higher rated voltage secondary tap, it carries more than its share of reactive current. Its compensator in turn causes the voltage relay to close and the tap changer to move to a still higher rated voltage tap. This still further increases its reactive current, and the process continues until the tap changer is in the maximum raise position. In a similar manner, the unit carrying the least reactive current will run to the maximum lower position.

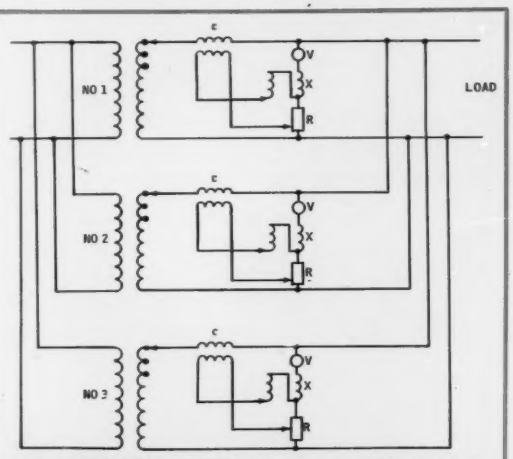
This operation may be avoided by the use of cross-current compensation, as shown in Figure 3. Here the current transformer of machine No. 1 is connected to the compensator of machine No. 2 and vice versa. With this connection, if machine No. 1 carries more reactive current because it is on a higher rated voltage tap, its effect on the compensator of machine No. 2 will cause machine No. 2 to move to a higher rated voltage tap and bring the two units closer together. Similarly, the reduced reactive current of machine No. 2 will cause machine No. 1 to move toward a lower rated voltage tap, also bringing the two units closer together.

This action will continue until the currents in the two machines are approximately the same. This circuit requires interconnection of the control circuits between machines. It is not applicable to more than two transformers operating in parallel.

Reversed reactance compensation may be used

For paralleling two or more transformers without control connections between machines, negative or reversed reactance compensation may be employed. As shown in Figure 4, the connections for each transformer are the same as those of Figure 2, except that only reactance compensation is used and the connections from the current transformer to the compensator are reversed. In operation, if one unit carries more reactive current because it is on a higher rated voltage tap, its compensator will cause the voltage relay to close its lower contacts. This causes the tap changer to move to a lower rated voltage tap. The machines are brought closer together and the load currents of the paralleled machines are more nearly equal.

This circuit requires no control connections between units. No changes in the control circuits are required



FOR LOADS NEAR UNITY power factor, positive resistance compensation and reversed reactance compensation used simultaneously regulate for equal currents. **(FIGURE 5)**

when a machine is taken out of service either by opening the secondary circuit breaker or by removing it completely for use on another load.

When only the secondary breaker is opened, the tap changer of the idle unit will regulate for a slightly higher no-load voltage than the full-load voltage of the load-carrying units. This slightly higher voltage is desirable when restoring parallel operation by closing the secondary breaker. One characteristic of this circuit is that, as the load current increases, the voltage held by the control on the output terminals of the transformers will decrease. That is, the output voltage decreases as the load current increases. This is undesirable unless the power factor of the load is near unity and the transformers are placed close to the load.

If the power factor of the load is close to unity, positive resistance compensation and reversed reactance compensation can be used simultaneously, as shown in Figure 5. The value of the resistance compensation can be increased to compensate for: (1) resistance drop of the line, (2) reactance drop in the line, and (3) the effect of the load current in the reversed reactance element of the compensator.

This circuit regulates for equal currents in the paralleled transformers in the same manner as described for reversed reactance compensation. In addition, it will maintain constant voltage at the load center for loads near unity power factor. It is not suitable for low power factor loads.

If one unit is removed from the line, the remaining units will regulate for slightly higher voltage because of the increased current through the resistance element of the line-drop compensator. If the secondary breaker of one unit is open, this idle unit will regulate for a slightly lower voltage than the load-carrying units. By changing the amount of compensation, the load-carrying units can be made to regulate for the same voltage as with all units in the bank.

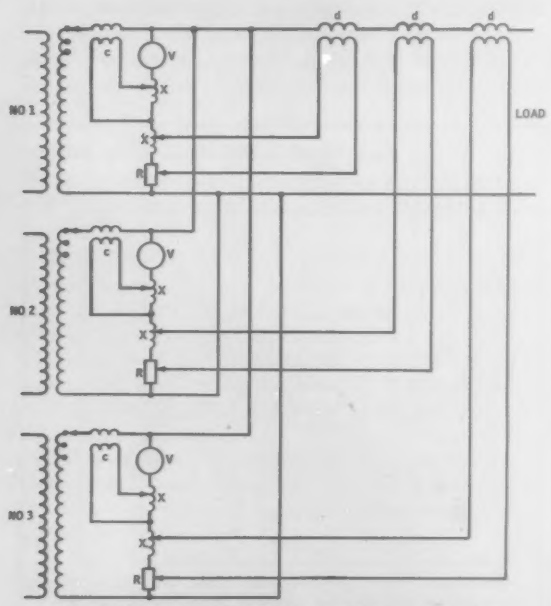
Compensating functions readily combined

Line-drop compensation for any kind of load can be added to the circuit shown in Figure 4 by using the total output current of all transformers to supply the positive resistance and reactance line-drop compensators of each transformer, as shown in Figure 6. The current of each individual machine is used to supply only the reversed reactance compensators. The setting of the reactance element of the line-drop compensator can be increased to compensate for the voltage introduced into the control circuit under balanced operation by the reversed reactance compensator. This function is in addition to compensating for reactive drop in the line.

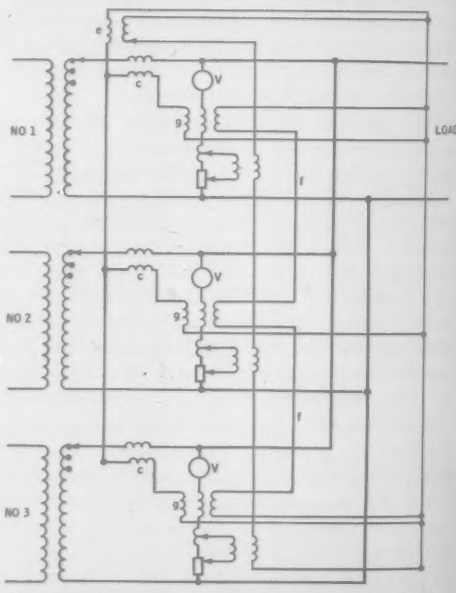
Where several transformers are to be operated in parallel, this is the type of circuit most frequently used. In actual practice there are many variations of the circuit illustrated in Figure 6. Nevertheless, the fundamental principles of operation are the same in all cases. These modifications are made to secure economies in cost of equipment and increased flexibility in operation. Usually, the total current is obtained as the sum of the currents in transformers *c* by connecting their secondaries in parallel. When this is done, the separate transformers *d* are not required.

If one of the paralleled transformers is removed from the bank, either completely or with only the primary connected, the load-carrying units will regulate for slightly lower voltages. In order to restore the load-carrying units to their former conditions, changes must be made in the compensator setting. If the idle unit is energized only on the primary side, it will regulate for a higher voltage than before.

One modification of the circuit of Figure 6 is shown in Figure 7. The total current for use in the line-drop compensator is obtained as the sum of the currents in transformers *c*. Its value is reduced to ⅓ by the use of



LINE-DROP COMPENSATION is added to circuit in figure 4 by using current from all transformers for resistance and reactance compensators. **(FIGURE 6)**



AN AUXILIARY current transformer is added to produce one-third the sum of currents in transformers c so its magnitude is right for compensators. **(FIGURE 7)**

the auxiliary current transformer *e* so it will be of proper magnitude for the line-drop compensator.

Negative reactance compensation, proportional to the regulator current combined with compensation for the effect of the balanced load current, is obtained by means of the three-winding reactor *g*. The voltage across the winding of reactor *g*, which is in series with the voltage relay *v*, is proportional to the voltage drop produced by the difference between the current from *c* and the currents flowing in line *f*. The circuit in line *f* is the component of current which is equal in all transformers. It is equal to the current in the primary of current transformers *c* divided by the number of transformers carrying load in parallel. The effect is the same as if the voltage drops due to the current in *c* and the current in *f* were subtracted separately. The performance of this circuit is the same as that diagrammed in Figure 6.

If a transformer is removed from the bank, either completely or with the primary remaining connected, no change in the setting of the line-drop compensators, or of the auxiliary transformer *e* supplying them, is required. When a transformer is disconnected from the load circuit, the winding of its current transformer *g*, connected to line *f*, must be short circuited so that the remaining units will operate in parallel as before. If the idle transformer is energized from its primary side, it will regulate for the same voltage as the loaded transformers.

Circuit modifications are possible

Another modification of the circuit diagrammed in Figure 6 is shown in Figure 8. The current used in the line-drop compensator is the sum of the currents in transformers *c*. This current is then divided into three equal parts by means of the transformers *g* for use in the line-drop compensator. Current is again divided into three equal parts by transformers *h* for obtaining negative reactance compensation.

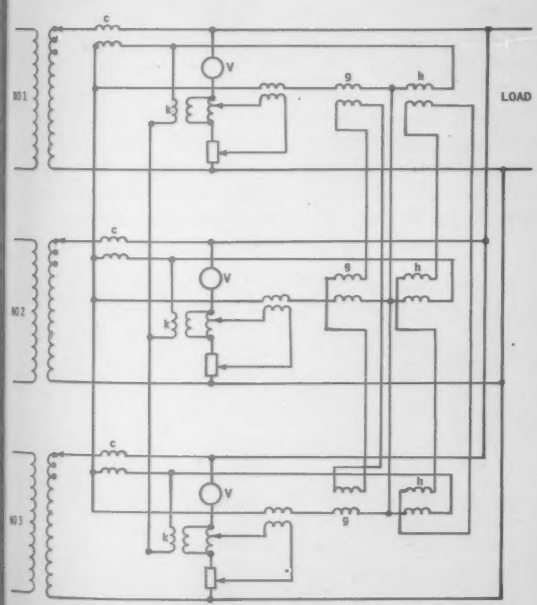
Negative reactance compensation and correction for load current is obtained by circulating the current from the transformer *k* through the reactance element of the line-drop compensator. The current in transformer *k* is the difference between the current in transformer *h* and the current in transformer *c*. The performance of this circuit is the same as that of the circuit shown in Figure 6.

If a transformer is removed completely from a bank, it is necessary that the individual line-drop compensators be reset to secure correct operation. Resetting is not necessary if the control circuit of the idle unit is left connected. When a transformer is disconnected from the load circuit, one winding of its current transformer *h* must be short circuited, its circuit through *k* opened. If this is done, the remaining units will operate in parallel as before. If the idle transformer is energized from its primary side, it will regulate for the same voltage as the loaded transformers.

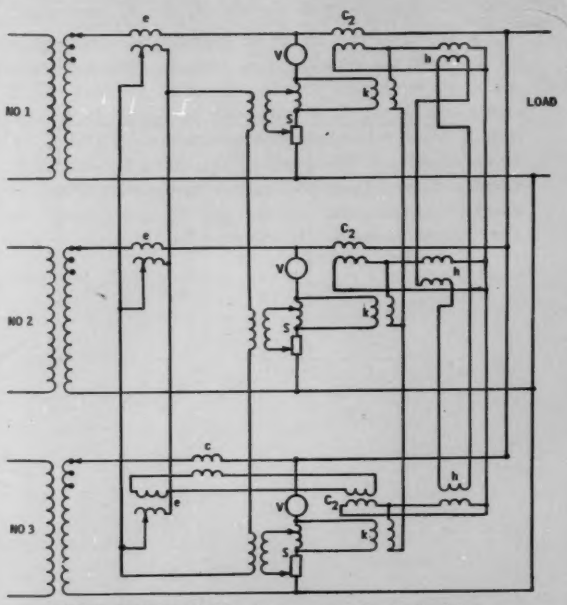
Another modification of the circuit of Figure 6 is shown in Figure 9. The total current for use in the line-drop compensators is obtained as the sum of the currents in the secondaries of transformers *e*. This current is circulated in series through the individual line-drop compensators *S*.

Negative reactance compensation, combined with correction for load current, is obtained by circulating the current from the transformer *k* through the reactance elements of the line-drop compensators. The current in *k* is the difference between the current in each transformer C_2 and the average current of all units, which is the current in transformer *h*. The performance of this circuit is the same as that of the circuit in Figure 6.

With the transformers removed from the bank, either completely or with only the primary connected, no change in the setting of the line-drop compensators or the transformers *e* supplying them is required. When a transformer is disconnected from the load circuit, the winding



CURRENT IS DIVIDED into three equal parts for negative reactance compensation by transformers *h* in this modification. **(FIGURE 8)**



TOTAL CURRENT for line-drop compensators is circulated in series through the individual line-drop compensators *S* in this modification. **(FIGURE 9)**

of its current transformer b must be short circuited so that the remaining units will operate in parallel as before. In addition, one winding of its current transformer k is open circuited.

Using individual current transformers e for three complete machines results in all machines being identical and reduces the amount of current which must be carried by the control wires between units.

In Figure 9, Units 1 and 2 have separate current transformers e and C_2 in the output lines. In most cases, the connections of Unit 3 would be used instead, with one main current transformer C and auxiliary current transformers e and C_2.

Tap changers can be locked in step

Satisfactory operation of paralleled load ratio control transformers may be accomplished by locking the tap changers in step. This control circuit keeps all tap changers at the same position except during transition periods when for a short time they may be one step apart. This control circuit differs from those previously discussed in that tap changers are not actuated by the current differential between transformers.

The general principle of operation for lock-in-step method is that, after moving one step, the leading machines will have their control circuits interrupted and their motors de-energized until lagging units catch up with them. A typical lock-in-step circuit is shown in Figure 10. The switches marked W are closed when the tap changers are on even numbered positions. The switches marked X are closed when the tap changers are on odd numbered positions. The motor starters marked S and T operate to move the tap changers in a direction to increase the voltage. The subscript "1" designates switches and relays applying to transformer No. 1, subscript "2" for machine No. 2, etc. Contacts R in the circuit are the "raise" contacts of the voltage control relay. O and E are relays connected as shown with normally closed contacts O_a and E_a respectively and normally open contacts O_b and E_b respectively.

The action of this circuit in keeping the transformers on the same tap position is as follows: When all units are on the same even position, all the W switches will be closed and all the X switches will be open. If the contacts R are closed by the voltage relay, relay coil E will be energized and lock itself in by closing its contact E_b. Contact E_a will open. All four S motor starters will be energized, causing the tap changers to move toward the next higher position. If machine No. 4 is the first to complete this operation, it will open switches W_4, de-energizing the starter S_4. It will close its contacts X_4, but because both O_b and E_a are open, no current will flow through the "odd" part of the control circuit, and the motor which operates tap changer No. 4 will stop. Tap changers on machines 1, 2 and 3 will continue to operate in like manner until all the tap changers are on the next even position. If the contacts R are still closed, the tap changer motors will again be energized, this time through the motor starters T_1, T_2, T_3, and T_4. Operation will continue as before, with the machine stopping on the next higher odd position and so on until the relay R opens its contacts, stopping all the mechanisms on the same position.

Similar circuits and switches are provided for operation of the machines in the opposite direction to lower the voltage. A single voltage relay and line-drop compensator, such as shown in Figure 2, is all that is needed for a complete bank of paralleled transformers using the lock-in-step method.

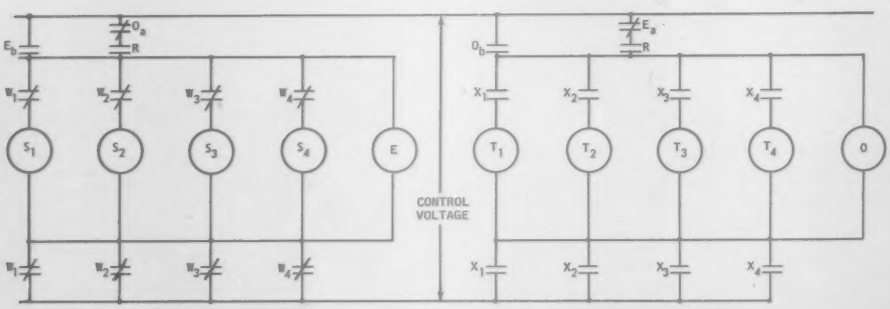
The disadvantage of the lock-in-step method is the number of mechanical switches, contactors and interconnections between units which are necessary.

Selecting a control circuit

The best procedure in selecting the scheme to be used for parallel operation of transformers is to choose the simplest scheme which will produce the desired results. The least complicated scheme described is reversed reactance compensation. Next in order of simplicity is reversed reactance compensation combined with positive resistance compensation. Neither of these schemes require control interconnections between machines.

Where these schemes do not give satisfactory results, and where only two machines are involved, cross-current compensation, which requires only two interconnecting wires per machine, is the least complicated. Where several machines are to be operated in parallel, a circuit providing negative reactance combined with positive resistance and reactance compensation, and which involves several interconnecting control wires between units, may be required.

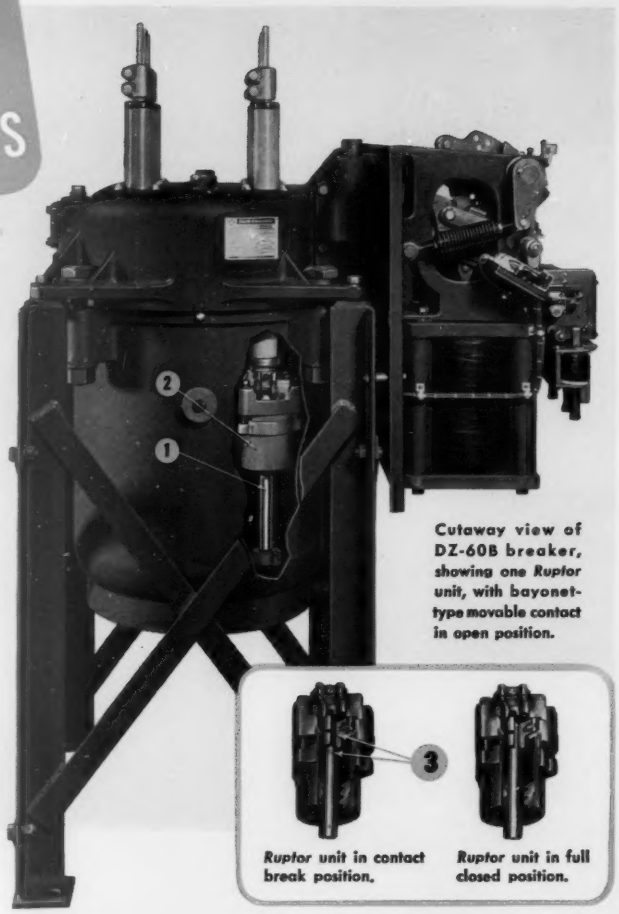
Where circuit conditions are such that none of the foregoing schemes are applicable, a lock-in-step or electrical interlock method may be necessary. Because of the greater number of relays and interconnections required, they are used only where one of the other methods is not applicable. Mechanical lock-in-step methods, while possible, are seldom used on modern machines.



LOCK-IN-STEP CIRCUIT keeps all machines together. Load ratio control mechanisms are kept on corresponding taps regardless of current differential. **(FIGURE 10)**

ALLIS-CHALMERS Type DZ Indoor Oil Circuit Breakers

CHECK THIS "Inside Story"



Cutaway view of DZ-60B breaker, showing one *Ruptor* unit, with bayonet-type movable contact in open position.

Ruptor unit in contact break position.

Ruptor unit in full closed position.

A LOOK INSIDE shows why years of dependable protection are assured with an Allis-Chalmers DZ breaker. Within the rugged frame and tank are time-proved *Ruptor* interrupting devices—which have their contacts controlled by a mechanically trip-free solenoid-operating mechanism. *Ruptor* units provide long periods of continuous, trouble-free service because they offer:

SIMPLE DESIGN: Bayonet contacts (1) are the only moving parts.

EASY INSPECTION: Drop the tank, and the bayonet contacts are visible in open position. For access to the stationary contacts, remove four bolts and cylindrical shell (2).

DEPENDABLE OPERATION: Tulip and bayonet type contacts (3) are self-aligning and self-cleaning; they maintain high conductivity without readjustment. Efficient interruption on special arcing-alloy contacts within oil-filled *Ruptor* unit minimizes arc energy—contributing to long contact life and low oil deterioration.

Allis-Chalmers circuit breakers are available in ratings from 2.5 to 230 kv, with interrupting capacities from 15,000 to 10,000,000 kva, to meet all industrial and power company requirements. For more information, call your nearby A-C representative, or write to Allis-Chalmers, Milwaukee 1, Wisconsin. A-3825

TYPE	RATED KV	MINIMUM KV AT RATED KVA	RATED AMPS	KVA INT. CAPACITY
DZ-40B*	7.2	2.3	600	100,000
			1200	100,000
			2000	100,000
DZ-60B†	13.8	4.0	600	150,000
			1200	150,000
DZ-100B†	13.8	4.0	1200	250,000
DZ-200B†	13.8	6.6	1200	500,000
			2000	500,000

*Ask for Bulletin 71B6179.
†Ask for Bulletin 71B6129.

Ruptor is an Allis-Chalmers trademark.

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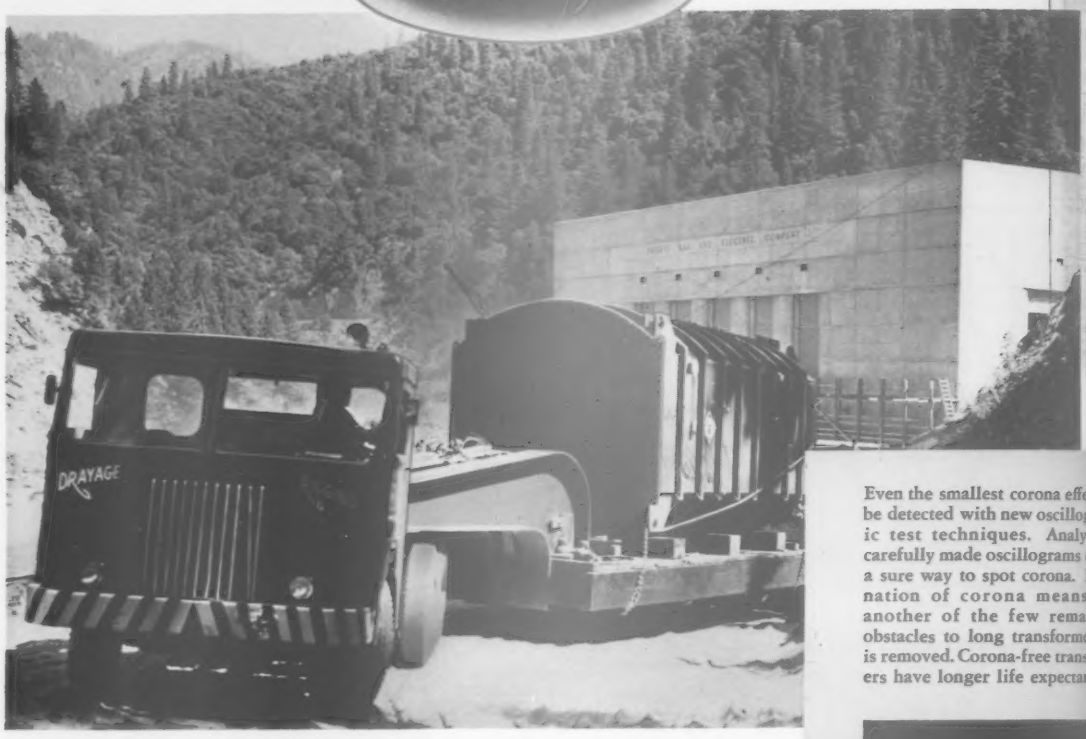
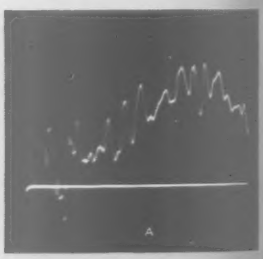
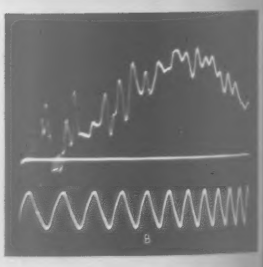


Even the smallest corona effect can be detected with new oscillographic test techniques. Analysis of carefully made oscillograms can be a sure way to spot corona. Elimination of corona means that another of the few remaining obstacles to long transformer life is removed. Corona-free transformers have longer life expectancy.





Corona discharge is often detected with neutral current measurement during impulse tests. These oscillograms indicate the existence of corona on a bare junction. They show (a) reduced current reading and (b) full neutral current reading.

It's Surprising How Costly Corona Can Be

CORONA CAN DROP insulation levels, once adequate, to below safe operating levels.

Corona can turn a normal switching surge into transformer breakdown. It ionizes, chars and deteriorates insulation.

Where insulation and windings meet . . . where metal parts change slope, voltage surges may create the starting point for corona.

But today, corona-free design is a reality. Engineers, aided by sensitive tests that spot the faintest traces of corona, have eliminated corona up to 100% of maximum test voltages. As a result your modern corona-free transformer has gained years of operating life.

Corona-free design provides the insulation levels, the strength and performance you can count on today and for years to come. Corona-free design keeps your transformer young. Allis-Chalmers, Milwaukee 1, Wis.

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